



## Chapter 1

# The Copernican Revolution

The Horse Head nebula in the Orion constellation  
(Reading assignment: Chapter 1)

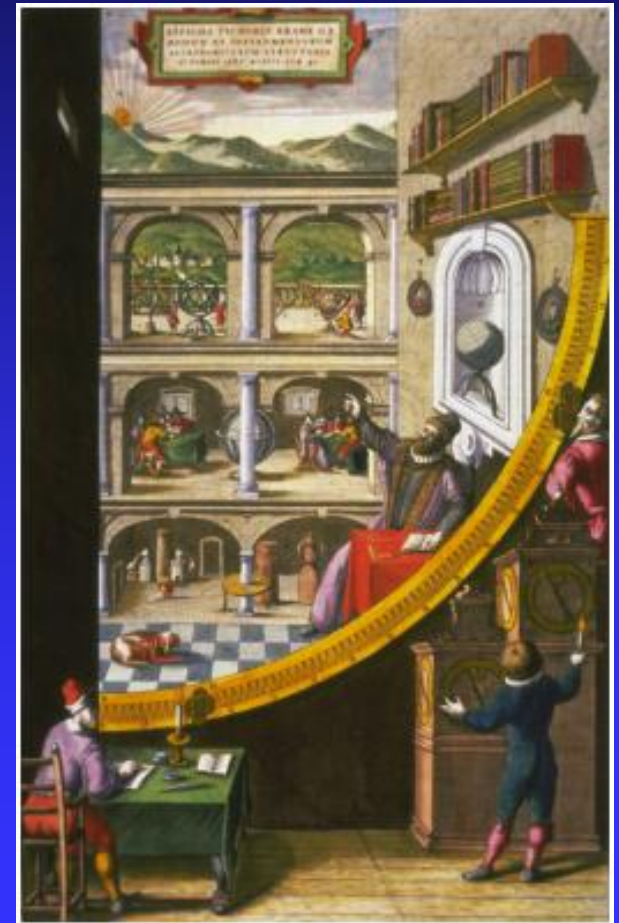
# Learning Outcomes

- How the geocentric model accounts for the retrograde motion of planets?
- What is the explanation of the retrograde motion of planets in the heliocentric model?
- Describe the main contributions of Copernicus, Tycho Brahe, Galileo and Kepler that lead to a modern model of the solar system (heliocentric model)
- Kepler's Laws of planetary motion
- How astronomers measure the true size (in kilometers) of the solar system
- Newton's Laws of motions and the Universal Law of Gravitation. How we can measure the mass of astronomical bodies ?

- The Sun, Moon and even the stars all move smoothly across the sky, with slight changes in brightness and position happening slowly over days and months or even years.
- Early observers noticed, however, that five bodies, called planets, moved somewhat differently.

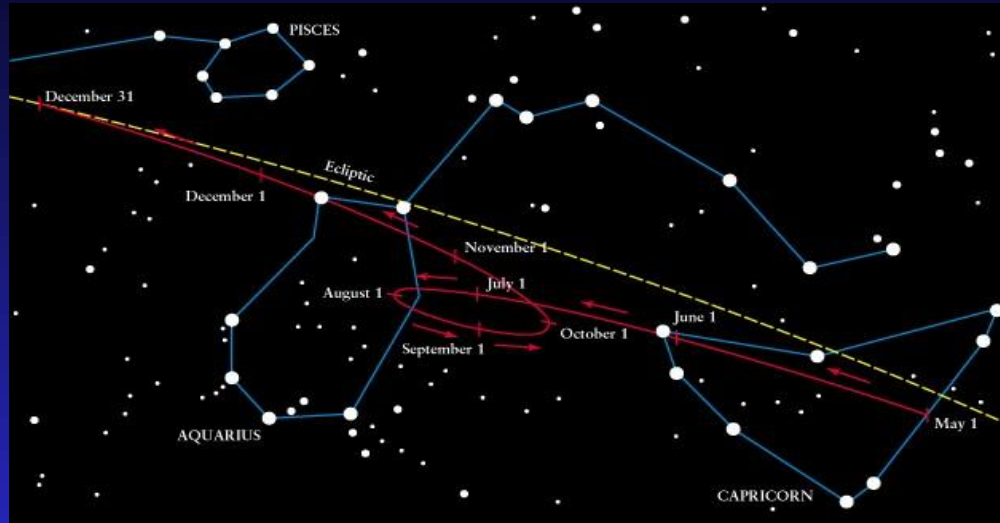
**Planets** seemed to "wander" across the Celestial sphere in two ways:

1. Direct Motion - normal eastward movement across the sky
2. Retrograde Motion – occasional westward movement, causing the planet to appear to make “loops”. Around the period of the retrograde motion, the planet get brighter



# Retrograde motion of Mars in the year 2003

All the planet outside the Earth's orbit (Mars, Jupiter, Saturn, Uranus and Neptune) behave in the same way  
The inner planets (Mercury and Venus) do something similar but the loops are around the position of the Sun



- Ancient observers noticed that a planet is brighter when it is in retrograde motion. They have to find an explanation to that. They correctly reasoned that the change in brightness is related to its distance from Earth
- Early observers used their observations to form ideas about the nature of the Universe.
- Astrology and Astronomy in ancient times were indistinguishable from each other. Both were interested to “see” into the future, but in a completely different way. Astrologers were interested in predicting the destiny of a person. Astronomers were interested in predicting the position of planets, the Moon and the Sun.
- As we will see in this chapter, finally astronomy replaced astrology and the modern astronomy and science was born.



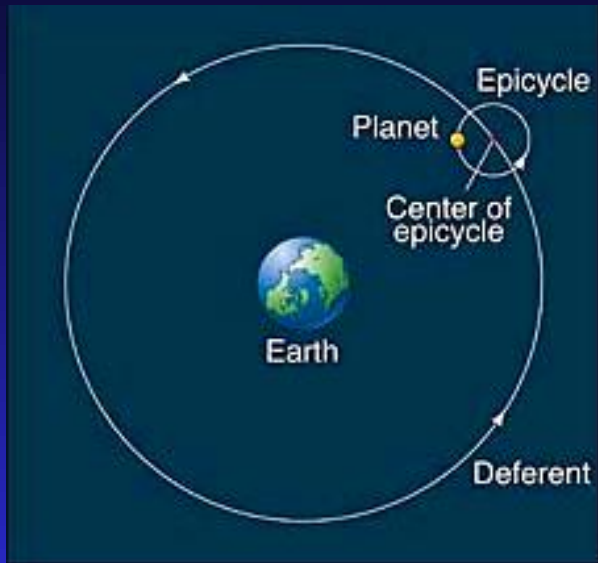
# The Geocentric Models



- Followed teachings of Greek philosopher Aristotle (384-322 B.C.)
- Geocentric model: Earth is at the center of the universe with planets and Sun orbiting it in circular orbits.
- Explained planetary motions using **deferents** and **epicycles**

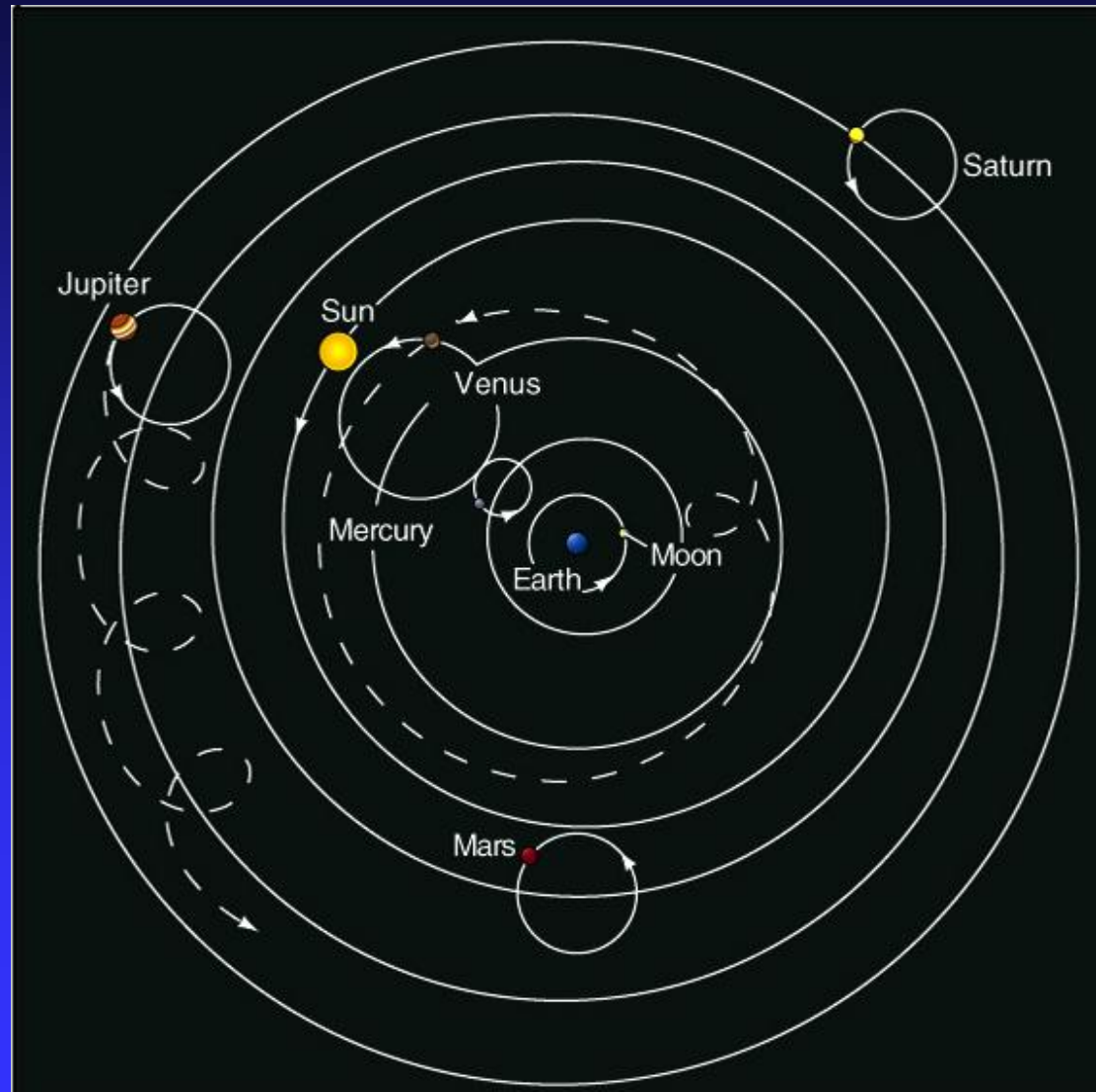
Ptolemy (AD 140) constructed one of the best geocentric models.

# Ptolemaic Universe



- Useful for predicting the positions of the five planets, Mercury, Venus, Mars, Jupiter and Saturn in the sky (At least within the accuracy of the observations at that time), but ultimately wrong.

The Ptolemaic model of the Universe survived for almost 13 centuries (140 AD to 1500 BC)



# Nicholas Copernicus (1473-1543)



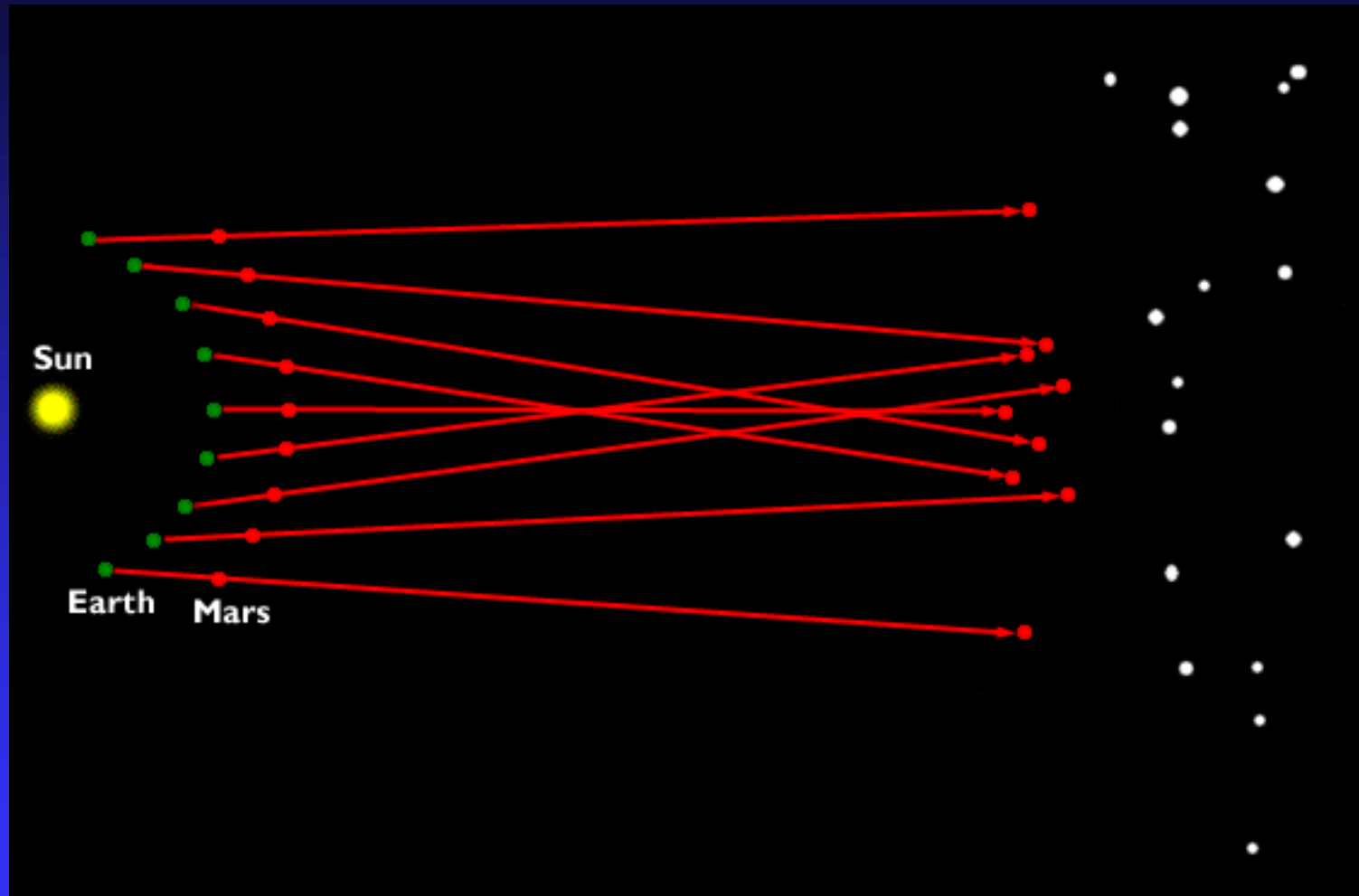
- Re-discovered Aristarchus (310-230 B.C.) idea of heliocentric model . Aristarchus proposed a model in which all the planets and the Earth revolve around the Sun. His ideas did not gain much acceptance; Aristotle influence was too strong.
- Copernicus introduced a mathematical model for a Heliocentric universe. The Sun is at the center of the universe.
- The critical realization that the Earth is not at the center of the Universe is called the “Copernican Revolution”
- Earth spins on its axis.
- Earth and all the planets orbit the Sun! (still on circular orbits)
- Only the Moon orbits the Earth.
- Retrograde motion is an “optical illusion.”

# Copernicus and the heliocentric model

- Copernicus idea were not widely accepted
- Relegating the Earth to a less important position in the solar system (and the universe) contradicted the conventional wisdom of the time
- It also violated the religious doctrine of the Roman Catholic Church. Getting in conflict with the church was not a good idea.
- His model was not much better than the geocentric model at predicting the position of the planets.
- There was no observational evidence to support his model and reject the geocentric model.
- For example, if the Earth revolves around the Sun, why we don't see stellar parallax?
- His book "On the Revolution of the Celestial Spheres" was not published until 1543, the year of his death
- It wasn't until the following century when Galileo (~1610) and Kepler were able to provided **observational** evidence that supported the heliocentric model



In the Heliocentric system, the apparent retrograde motion of the planets is naturally explained.



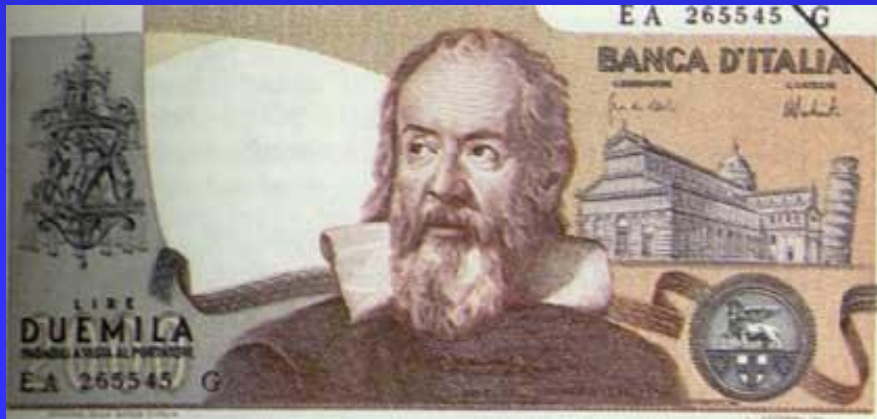
A planet *appears* to undergo retrograde motion when the Earth approaches and ‘overtakes’ that planet in its orbit.

# The Birth of Modern Astronomy

Galileo Galilei (1564-1642)

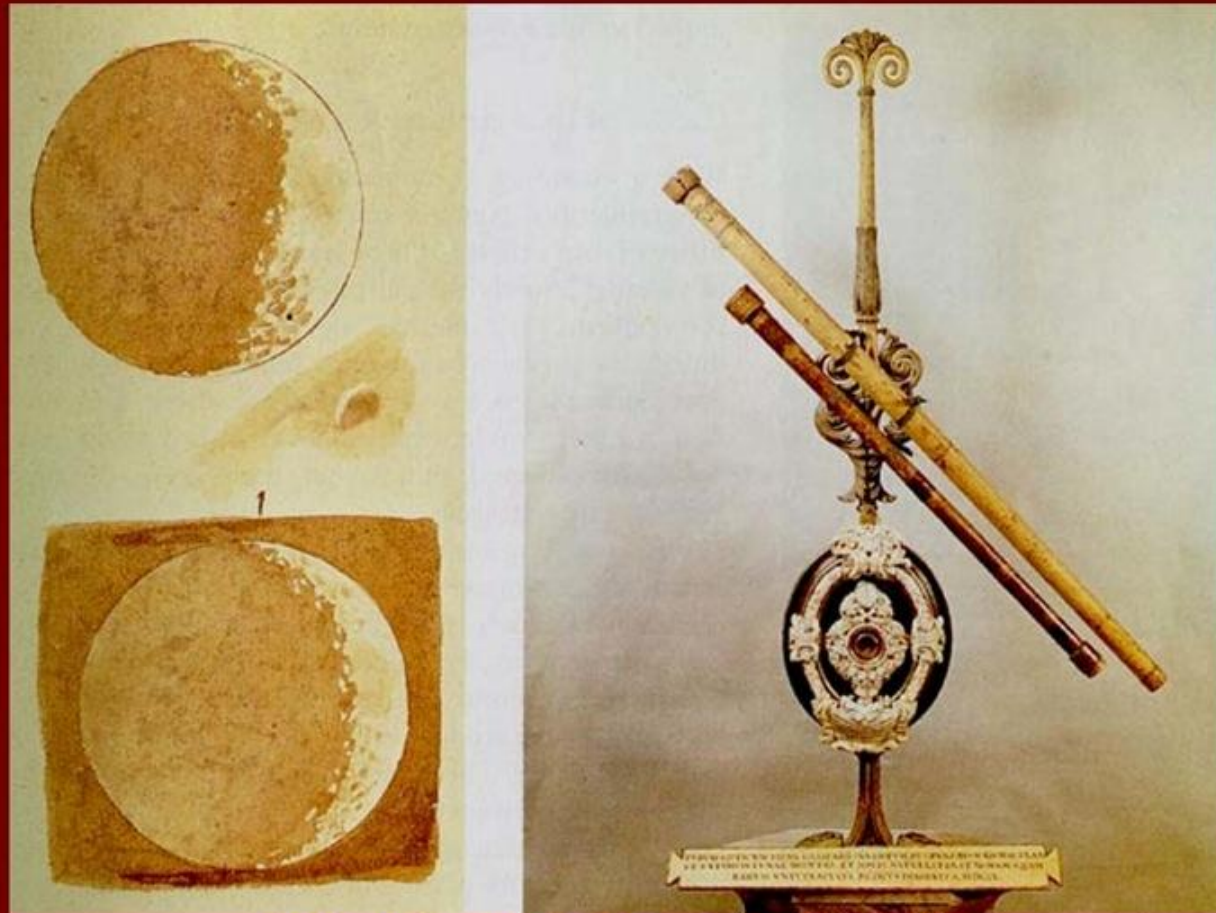


- Father of experimental science
- First to point a telescope (which he built) toward the sky in 1609
- Discoveries:
  1. Moon craters and mountains
  2. Sunspots and the rotation of the Sun
  3. Satellites (Moons) of Jupiter
  4. Phases of Venus



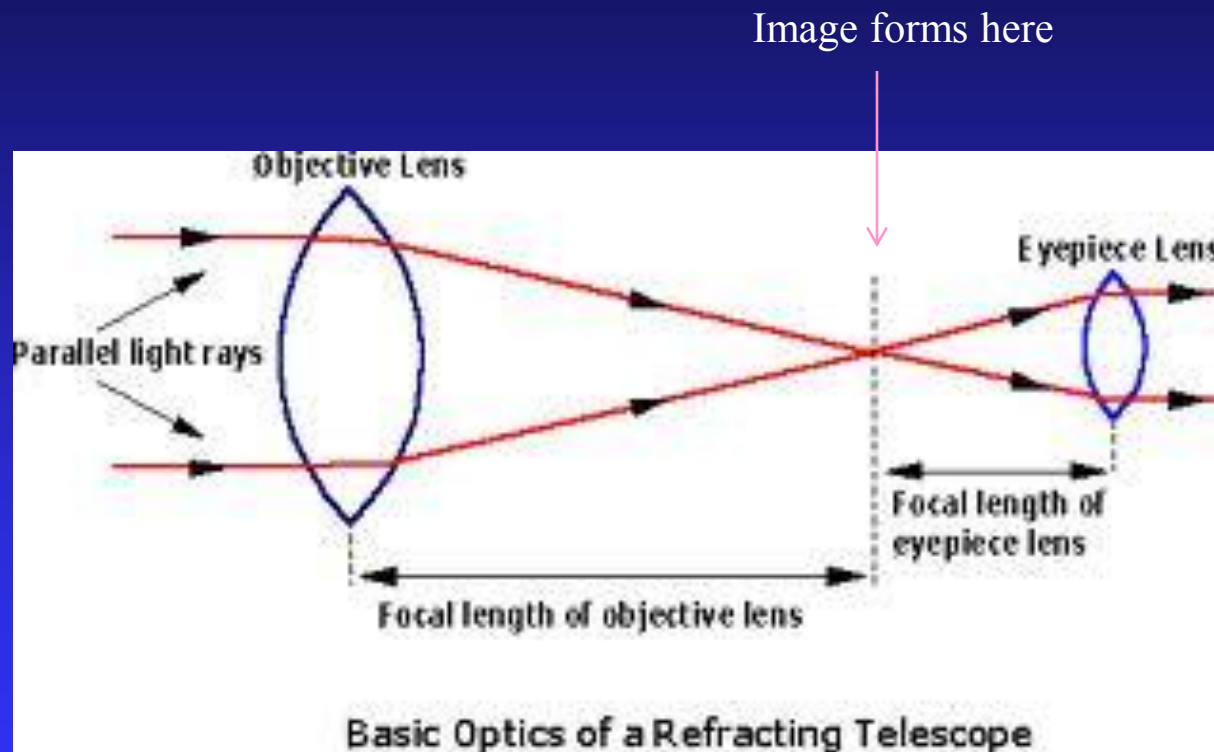
# Galileo telescope

( A refracting telescope, magnification of 20)



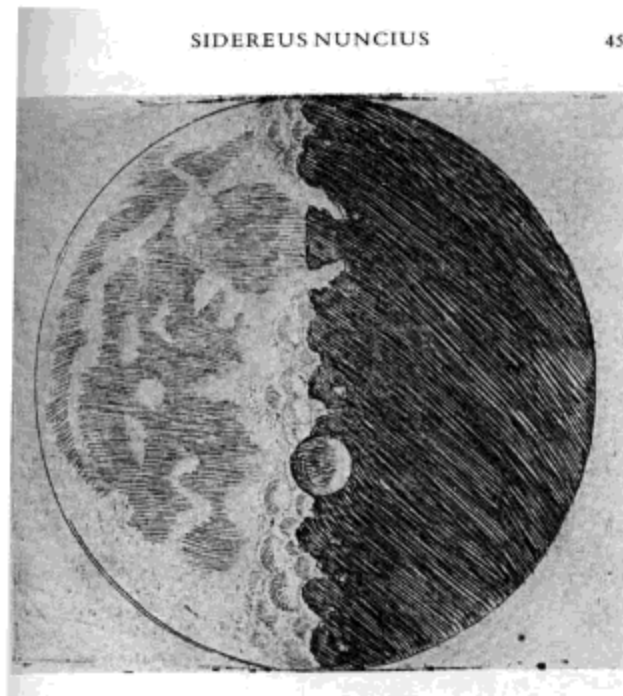
*Mountains on the Moon, seen by Galileo  
with his self-constructed 20X telescope*

# The basic optics of a refracting telescope





Galileo found that the Moon has mountains, valleys and craters. Features not too different from those on Earth



Galileo sketch of the Moon

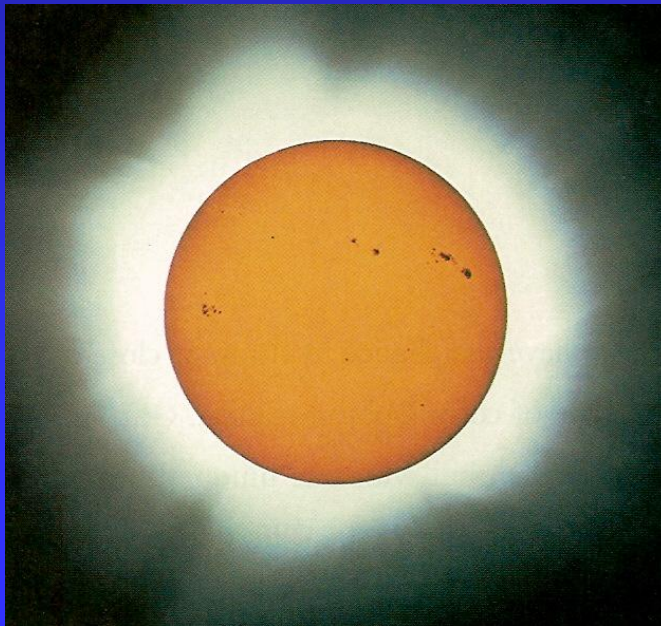


Moon about 7 days old

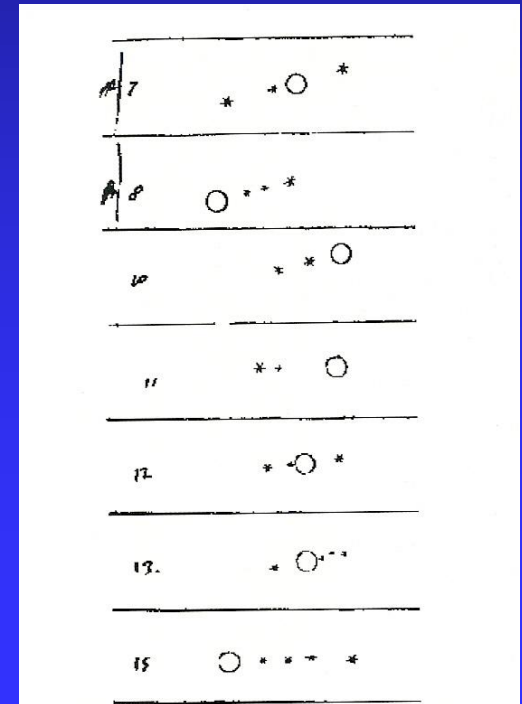
Crater Albategnius

# More about Galileo observations and their implications

The Sun has imperfections, it wasn't a perfect unblemished sphere. He found that it had dark spots now known as *sunspots*. Over a few days, the sunspots drifted across the disk, evidence of rotation of the Sun (about once per month)



Jupiter has four satellites (Now known as Galilean moons): Io, Europa, Ganymede and Callisto. They were in orbit around Jupiter, not around the Earth

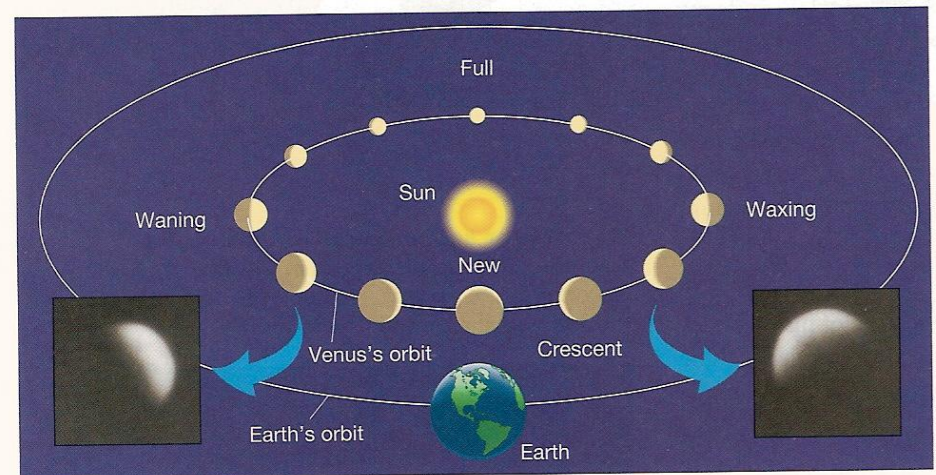


# More of what Galileo observed and the implications

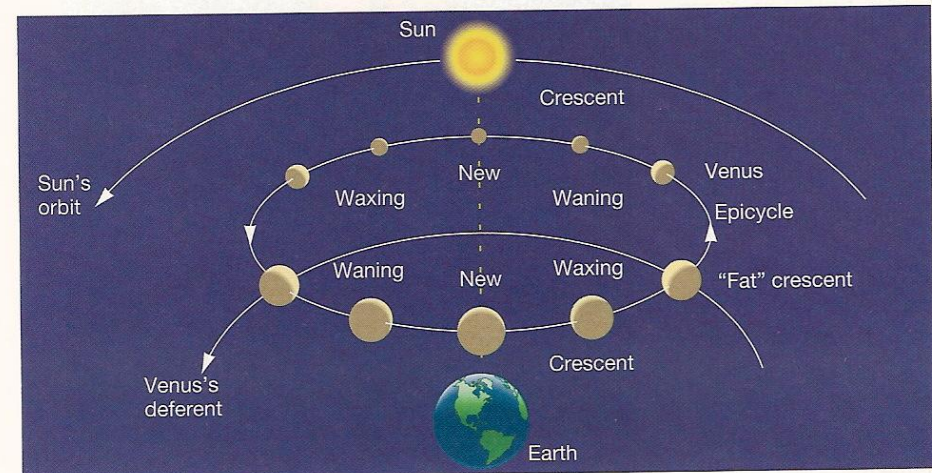
Found that Venus had a disk  
Venus phases: Venus show a complete cycle of phases, (similar to the Moon) from “new” Venus to “full” Venus

In the **heliocentric** (Sun-centered) model, it was simple to explain the “full” phase of Venus

Using the **geocentric** (Ptolemy’s) model, some phases of Venus had no explanation. In this model, Venus cannot go through a “full” Venus phase



(a) Sun-centered model



(b) Ptolemy's model



## Galileo observations contradicted the geocentric model:

- Venus did not orbit the Earth. It orbits the Sun
- Jupiter's satellites did not orbit the Earth. They orbit Jupiter

Galileo observations challenged the “scientific” orthodoxy and the religious dogma of the day.

His ideas were judged heretical. He has to appear before the Inquisition in Rome. He was forced to retract his claim that Earth orbit the Sun.

The Inquisition put him in house arrest for the rest of his life.

Galileo used the **Scientific Method** when studying objects in the sky.

Observation → Explanation



Prediction



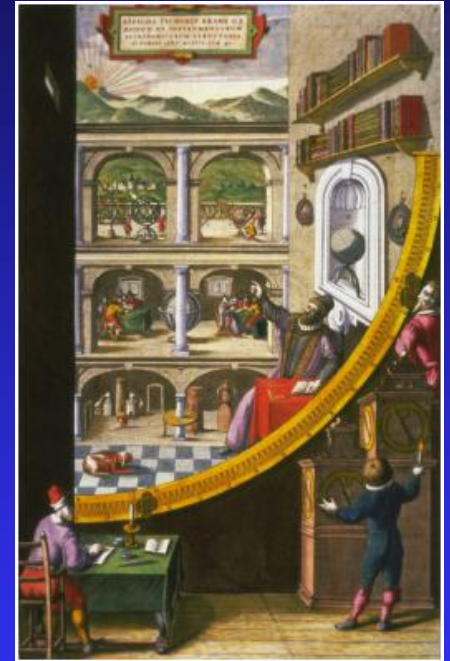
# The Laws of Planetary Motion

## Tycho Brahe (1546-1601)

- Recorded superb naked-eye positions of the planets.



Tycho Brahe (a Danish) was an excellent observational astronomer. In his observatory named Uraniborg in the island of Hven, (off the coast of Denmark), he built large instruments with large circles that allow him to observe the position of planets and stars with good accuracy. His instruments had no optics, they were just sighting devices.



Tycho died in 1601, about 8 years before the use of telescopes for astronomical observations (1609)

- Around 1600 Tycho became an employer of Kepler who eventually inherited all of his data after his death.

# Johannes Kepler (1571-1630)



He published his first two laws in 1609, close to the time Galileo was using his telescope

- Kepler goal was to find, within the framework of the Copernican model, a way to fit Tycho Brahe's data and be able to describe the shapes, relative size of the planetary orbits.
- He did not observe, was a pure theorist!

He used the observing data collected by Brahe

- Using the Copernican heliocentric model, he struggled trying to fit the observations using circular orbits. It didn't work!
- To fit the observations, he had to assume that planets are on elliptical orbits

**His three laws of planetary motions are empirical (Based on fitting to the existing data)**

# Kepler's First Law

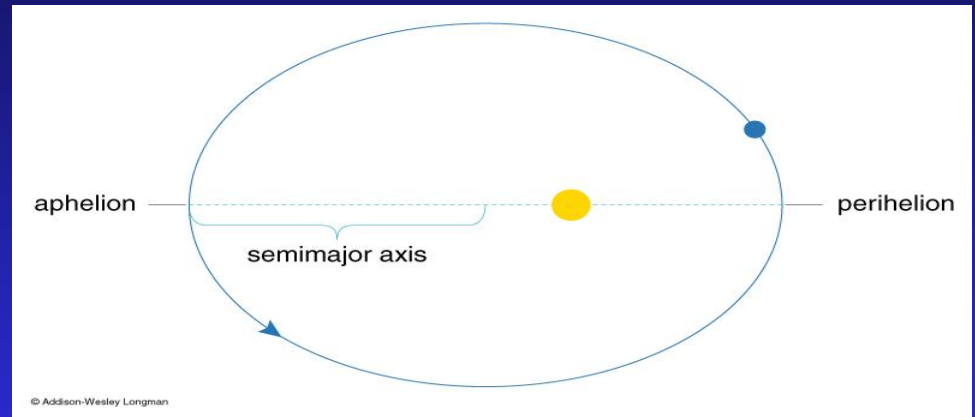
- The orbital path of the planets are elliptical with the Sun at one focus.

**Perihelion:** shortest distance from the Sun

**Aphelion:** largest distance from the Sun

Ellipse, definition of eccentricity:

$$\text{eccentricity} = \frac{\text{major axis} - \text{minor axis}}{\text{major axis}}$$



In general, all orbiting bodies follow elliptical orbits. This applies to the Moon, planets, binaries stars, satellites orbiting planets and all orbiting bodies.

# Important parameters in the ellipse

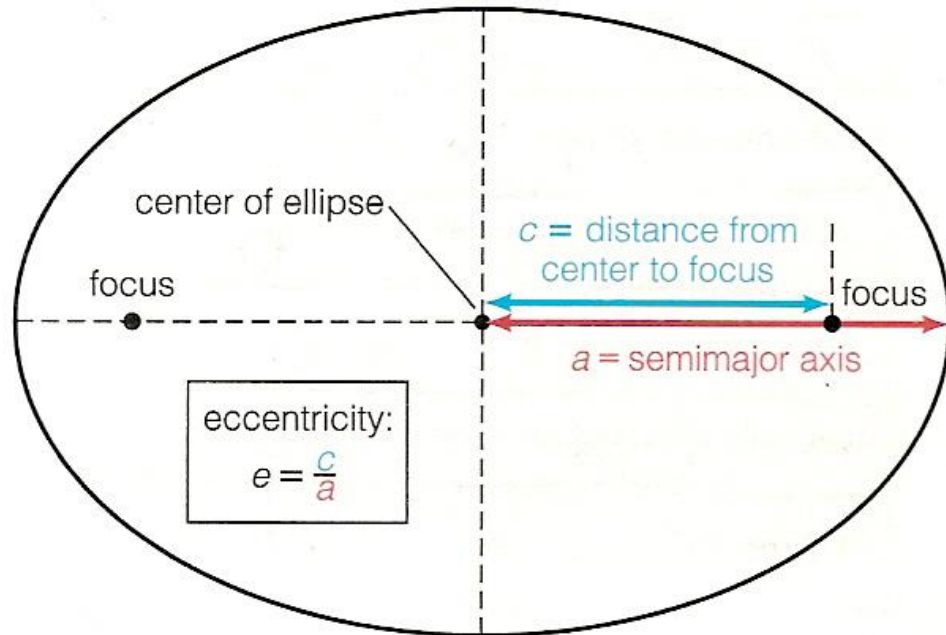
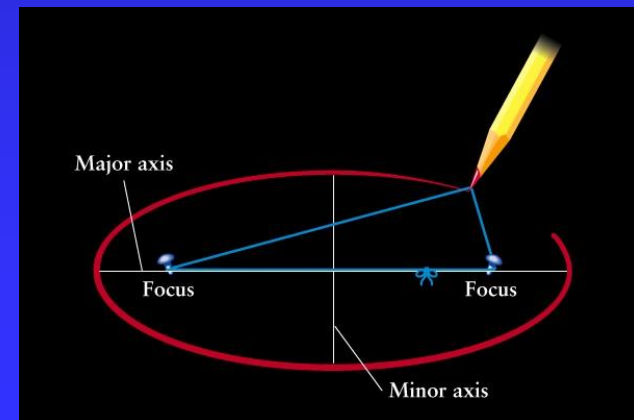


FIGURE 1

In a **circle**, the position of the two foci coincide with the center. In that case, the distance **c** is **zero** and the eccentricity **e** is **zero**

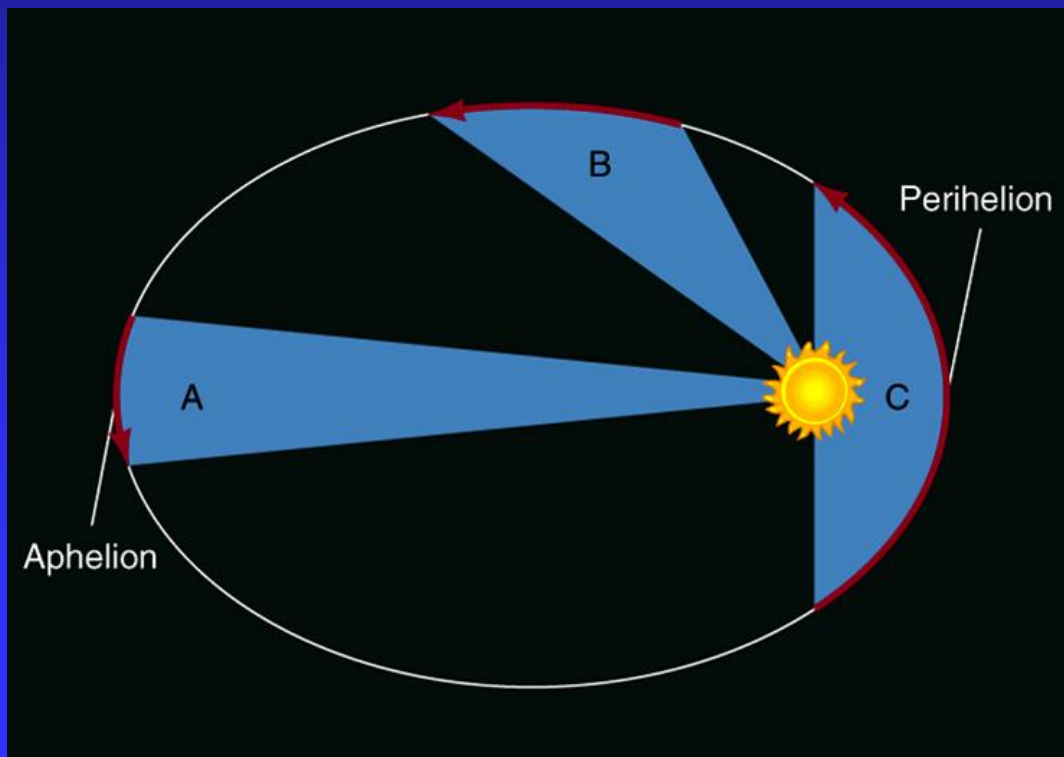
How to generate an ellipse:





# Kepler's Second Law

- An imaginary line connecting the Sun and any planets sweeps out equal areas of the ellipse in equal intervals of time.
- As a result from applying the second law, the planets move fastest at perihelion and slowest at aphelion.



## Important implication of the Second Law:

$$\text{area A} = \text{area B} = \text{area C}$$

The length of the arc for area C is longer than the length of the arc for area A but the planet travel through these two arcs in the same amount of time



It travel faster to cover area C

# Kepler's Third Law

- **The square of a planet's orbital period is proportional to the cube of its semi-major axis.**
- If the period is expressed in **years** and the semi-major axis in **AU**, the proportional sign can be replaced by the equal sign

$$P^2 = a^3$$

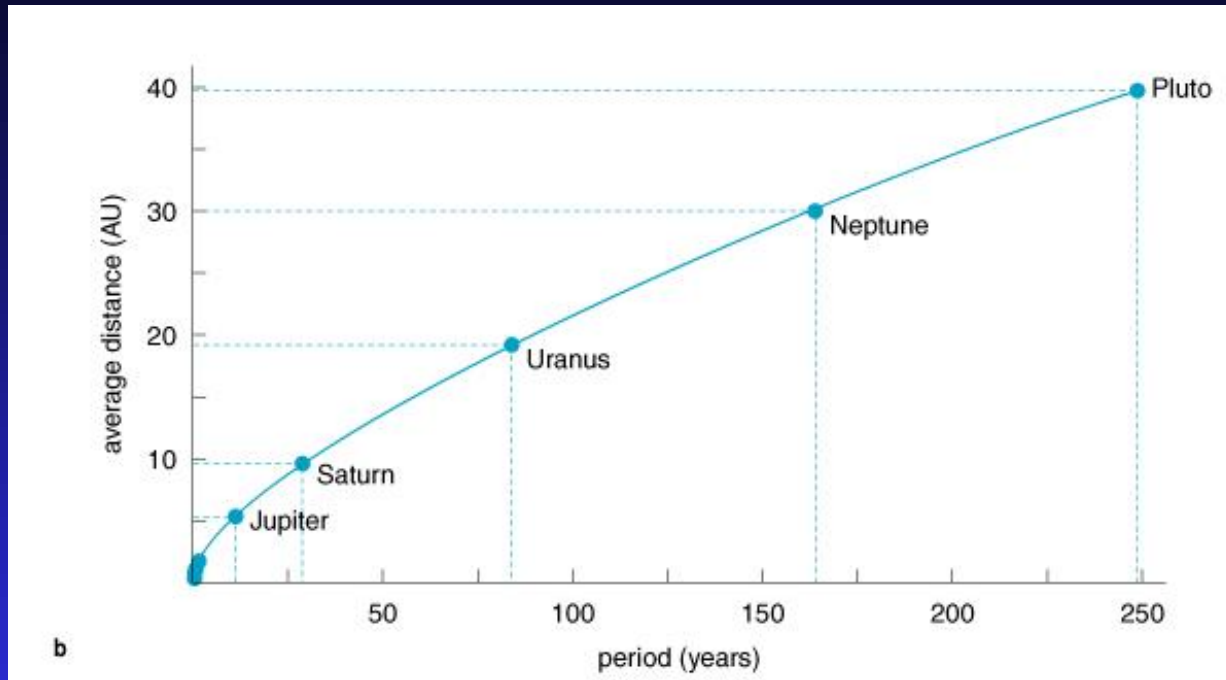
**P** (Period in **years**) = time for one orbit

**a** (Semi-major axis in **AU**) = average distance

(**a** corresponds to the radius if the orbit is circular)

Kepler derived this law using data from Mars. He later extended the law to the rest of the planets known to him

## Let's plot Kepler Third Law



$$P(\text{period})^2 = a(\text{semi-major axis})^3$$

The largest the distance between the planet and the Sun, the longest the period of the planet

$$P^2 = a^3$$



$$P^2 / a^3 = 1$$

# Some orbital properties of the planets

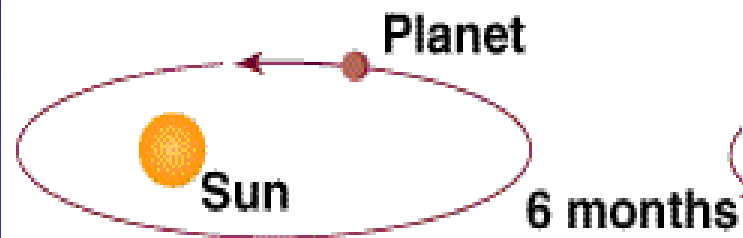
**TABLE 1.1** Some Planetary Properties

PLANET	ORBITAL SEMI-MAJOR AXIS, $a$ (astronomical units)	ORBITAL PERIOD, $P$ (Earth 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
Pluto	39.48	248.0	0.249	0.999

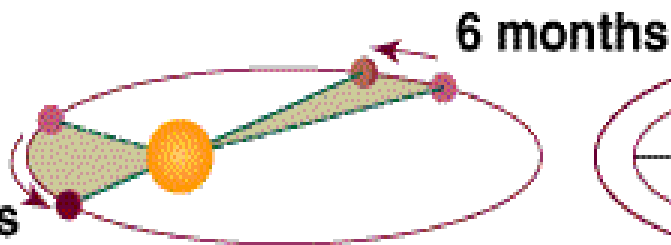
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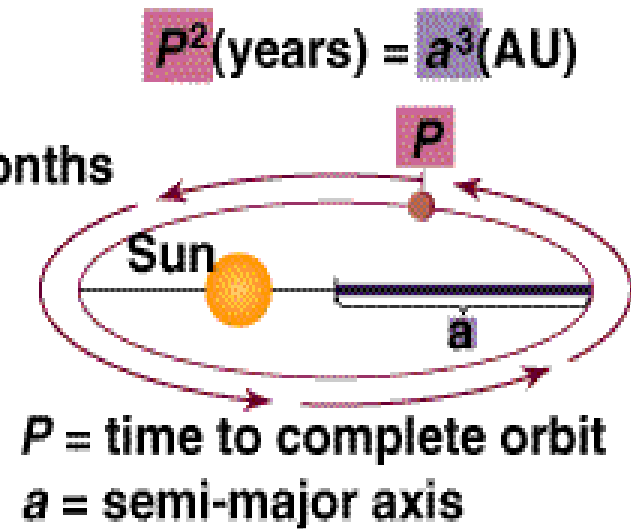
# Kepler's Laws



1<sup>st</sup> Law



2<sup>nd</sup> Law



3<sup>rd</sup> Law

# Kepler's Third Law, an example

- The orbital period **p** of the Earth is 1 year and the distance **a** to the Sun is 1 AU
- What is the orbital period  $P$  (or the “year”) of a planet located at a distance of  $a = 10$  AU from the Sun?
- Should the period be 10 years?

If  $a = 10$  AU then,  $P = 10$  years

Let's find the answer:

Let's use Kepler's Third Law

$$P^2 = a^3$$

$$a = 10 \text{ AU}$$

$$P^2 = 10^3 = 1000$$

$$P = \sqrt{1000}$$

$$P = 31.5 \text{ years}$$

# The dimensions of the Solar System

**Kepler's Laws** tell us the shape of the each planet's orbital motion, the period and relative distance to the Sun (In AU ) but it doesn't tell us about the actual size of the orbit (in kilometers). How many kilometers is one AU? How we can determine that?

The modern method to determine the actual distances in the solar system is RADAR (Acronym for RAdio Detection And Ranging). A short pulse of radio waves is directed towards a planet (for example to Venus). The wave is reflected at the planet and we get a weak return pulse (echo). We can measure the time that the radio wave takes for the round trip. Since we know the speed of light ( $c = 300,000 \text{ km/s}$ ) we can derive the distance ( $d = c \times t$ ). The time  $t$  here is half of the round trip time.

Note: We cannot directly measure the AU by bouncing radio waves directly to the Sun. Radio waves are absorbed by the Sun!

# Example

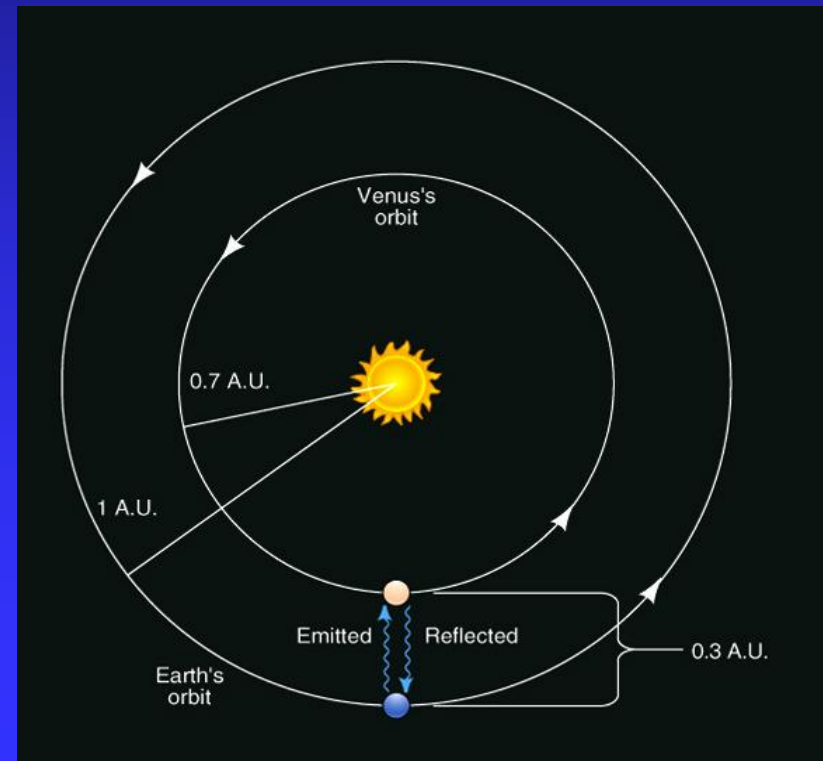
We send a radar pulse to Venus when it is at the closest point from Earth. It takes about 300 seconds to receive an echo. The one-way travel time is 150 seconds. Venus is 0.3 AU from Earth at the closest point.

(Remember that  $\text{Speed} = \text{Distance} / \text{Time}$ )

$\text{Distance} = \text{Speed} \times \text{Time}$

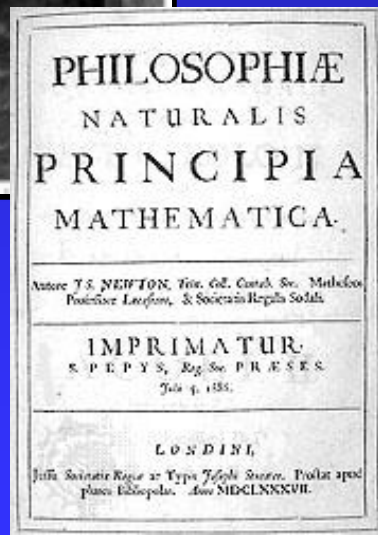
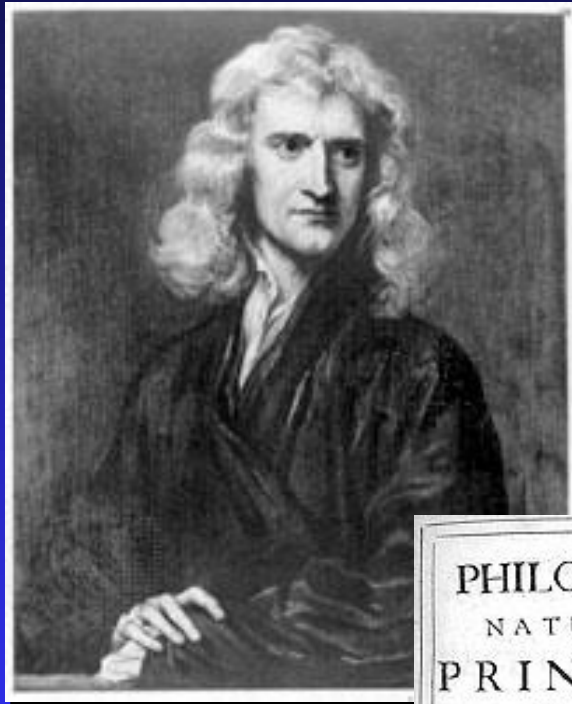
$\text{Distance} = 300,000 \times 150 = 45,000,000 \text{ km}$

The AU is  $45,000,000 / 0.3 = 150,000,000 \text{ km}$





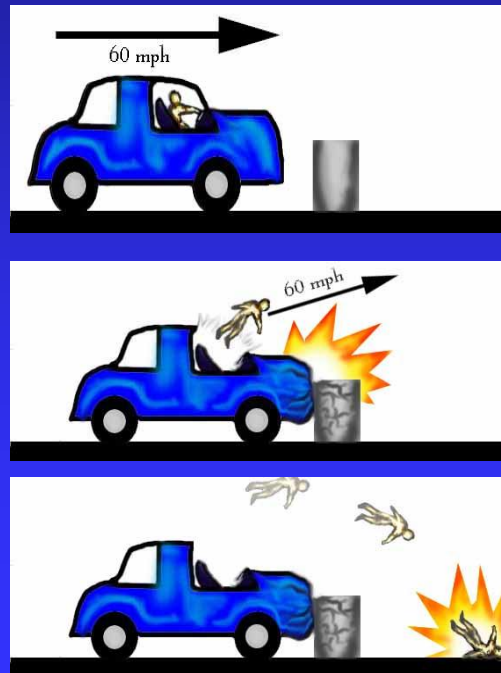
# Isaac Newton (1642-1727)- 17th Century British mathematician



- Developed what is now known as “Newtonian mechanics.”
- His 3 laws of motion plus his theory of gravity and his development of calculus are sufficient to explain virtually all motion, including planetary motions.
- Only in extreme cases do these laws of motion break down.

# Newton's First Law

An object at rest remains at rest, and a moving object continues to move forever in a straight line with constant speed, unless some **external force** changes their state of motion.



Why the driver didn't move in a straight line?

## Newton's Second Law

The acceleration of an object is directly proportional to the net applied force and inversely proportional to the object's mass ( $a = F/m$ )

$$F = m a$$

If two object are pulled with the same force, the one with the *greater mass* will accelerate *less*.

$$m \mathbf{a} = F = \mathbf{m} a$$

If two identical objects (same mass) are pulled with different forces, the one pulled with the *greater force* will accelerate *more*.

Remember the definition of speed and acceleration:

Speed = Distance/Time (Units: m/sec)

Distance = Speed x Time

Acceleration = Speed/Time (Units: m/sec<sup>2</sup>)

# Newton's Third Law

“Whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first.”

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

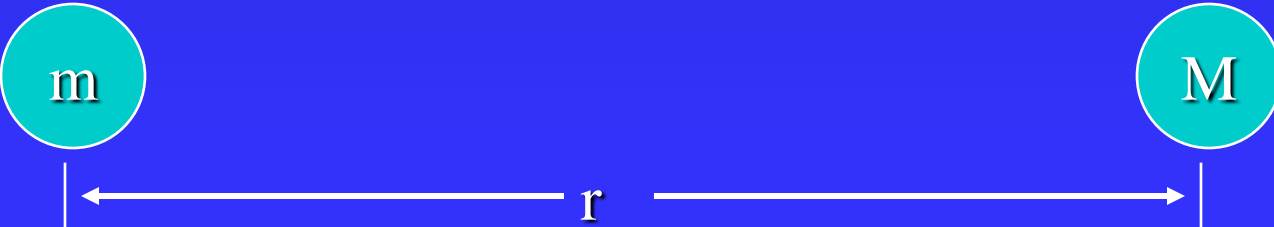
# Gravity

Newton realized that any object having **mass** exerts an attractive gravitational force **F** on all other objects having **mass**.

$$F = \frac{GMm}{r^2}$$

Diagram illustrating the gravitational force equation:

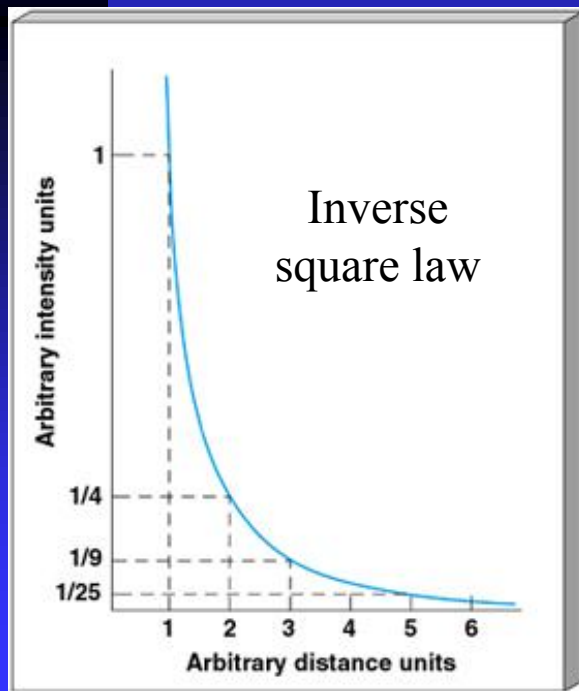
- F**: force
- G**: constant
- M**: Mass of one object
- m**: Mass of other object
- r**: Distance between them





# Newton Law of Gravitation

The gravitational force **F** between two bodies is directly proportional to the product of the masses **M** and **m** and inversely proportional to the square of the distance **r** between them



$$F = \frac{GMm}{r^2}$$

Labels for the equation:

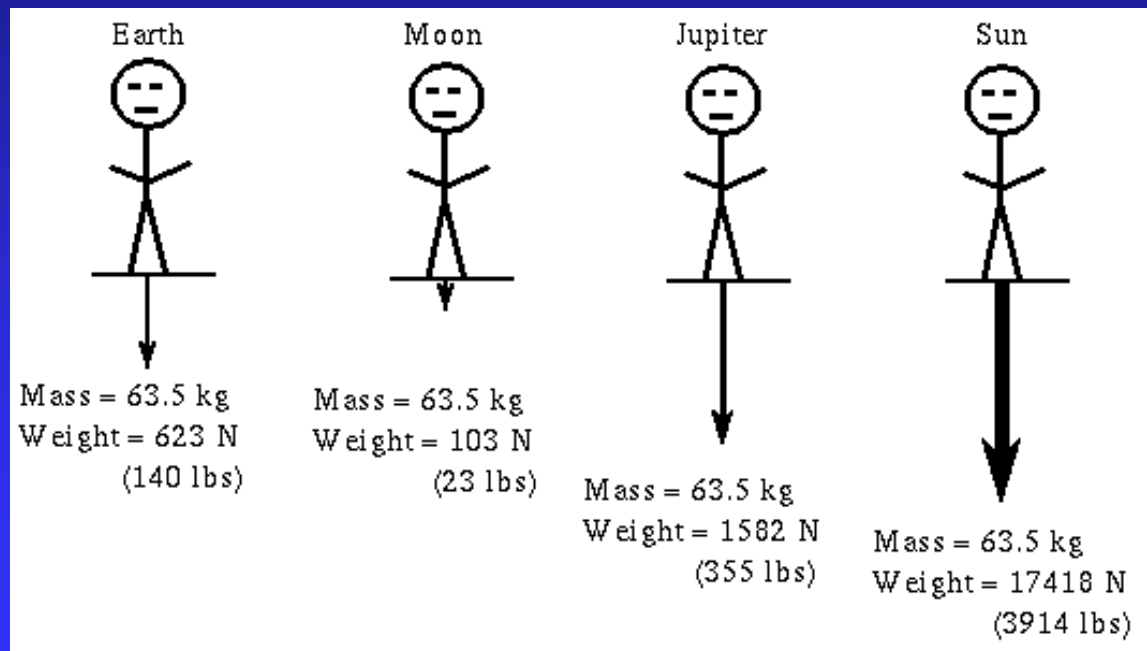
- Mass of one object (points to  $M$ )
- Mass of other object (points to  $m$ )
- constant (points to  $G$ )
- force (points to  $F$ )
- Distance between them (points to  $r$ )

# Weight and Mass

**Weight** is the force due to the gravitational attraction of a body by the Earth (or by another body).

**Mass** is the amount of matter

You would weigh less on the Moon (weaker gravitational force) than on Jupiter or the Sun:



N  $\Rightarrow$  Newton  
a unit of force

**Note:** Mass  $\neq$  weight: In the example, the person's mass never changes but the weight does.

# The mutual gravitational attraction between the Sun and planets is responsible for their motion.

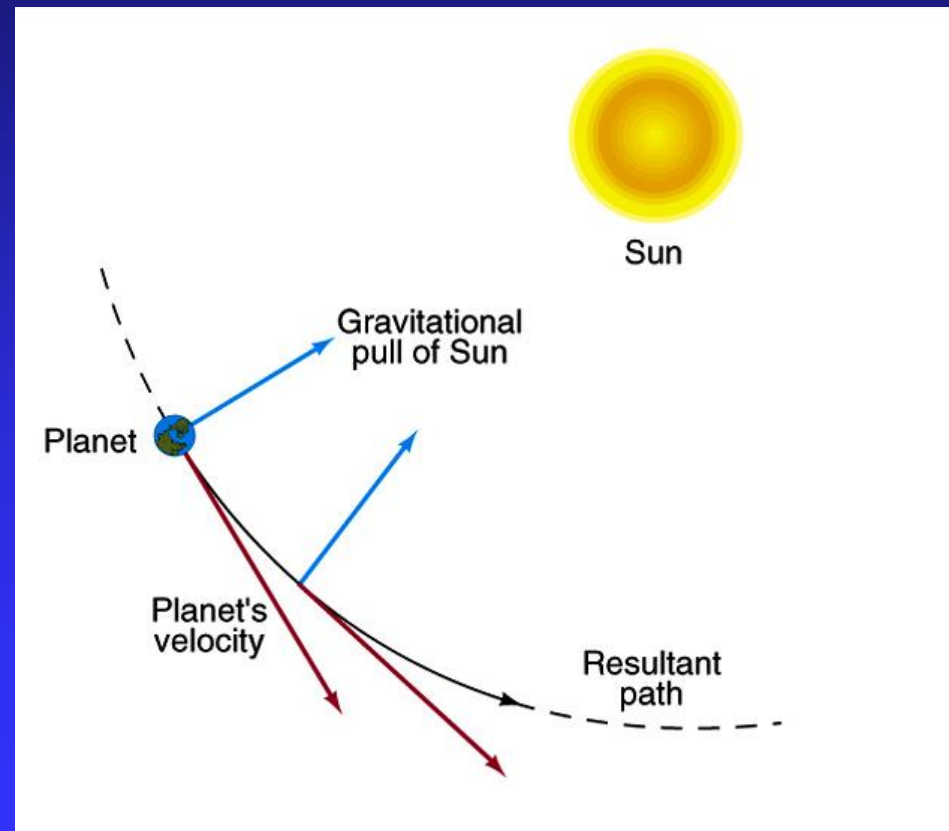
The gravitational pull of the Sun forces the planet to change the direction of the velocity.

At every point in the planet's orbit, the **direction** of the gravitational force exerted by the Sun changes when the planet moves in its orbit. That changes the **direction** of the velocity of the planet.

If the planet moves a small amount (an infinitesimal) in its orbit, the direction of the gravitational force changes and as a consequence, the resulting direction of the velocity changes.

To solve the problem and compute the trajectory of the planet over all the small steps, it was necessary to invent **Calculus**. Newton and other physicists and mathematicians invented Calculus.

To compute the orbit it is necessary to “integrate” over the small changes



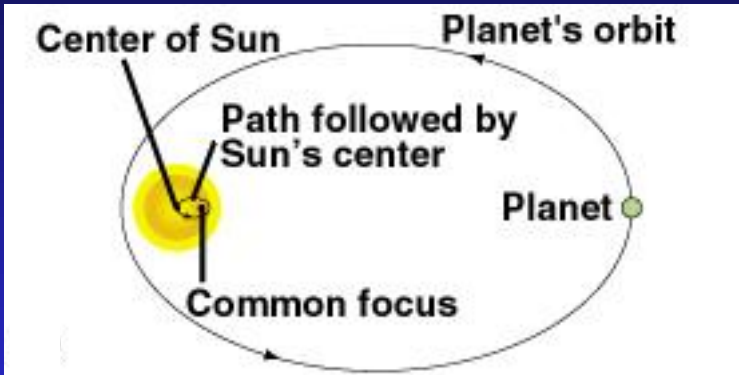
# Kepler's 3rd Law revisited

Newton's laws of motion and his law of universal gravitation provided a theoretical explanation for Kepler's empirical laws of planetary motion

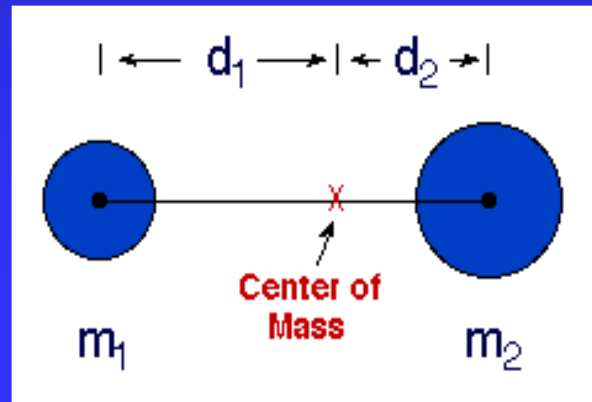
Using Newton's universal gravitation law, one can derive Kepler's laws. But the equations are more general and allow to extend the results to any two bodies orbiting each other.

The Sun and Earth both orbit their mutual center of mass, which is *inside* the Sun.

The Sun moves very little (BIG mass), while the Earth moves a lot (less massive).



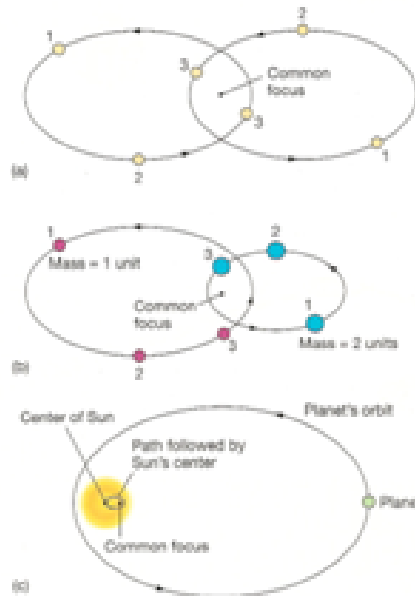
What is the **Center of Mass**? →



$$m_1 d_1 = m_2 d_2$$

# Orbits of bodies of different masses

## Orbit of bodies of different mass



- Two stars of about the same mass orbit around each other describing two ellipses of the same size
- Two stars with different mass, orbit around each other. The lowest mass star describe a larger ellipse.
- A star and a planet orbit each other. Because of the lower mass of the planet, the orbit of the planet is a large ellipse. Due to the large mass of the star, the center of mass is close (inside) the star. But the star also describe a small ellipse

An example:  
The mass of the Sun is about 333,000 times larger than the mass of the Earth

Revised Kepler's First Law:

**The orbit of a planet around the Sun is an ellipse having the center of mass of the planet-Sun system at one focus.**



The revised Kepler's 3<sup>rd</sup> law include both the mass of the central body and the mass of the orbiting body.

The change to Kepler's third law is small in the case of a planet orbiting the Sun, but larger in the case where the two bodies are closer in mass, e.g. 2 stars orbiting each other (binary star system).

Kepler's revised 3<sup>rd</sup> law:

$$P^2 \propto \frac{a^3}{M_{\text{total}}}$$

( $\propto$ : Proportional sign)

For Planet-Sun systems:

$$M_{\text{total}} = M_{\text{Sun}} + M_{\text{planet}} \approx M_{\text{sun}}$$

# Kepler's revised 3<sup>rd</sup> Law

$$P^2 \propto a^3 / M_{\text{total}}$$

If we express the period **P** in **years**, the distance **a** in **AU** and the mass **M** in **solar mass**, we can substitute the  $\propto$  by an  $=$  sign

$$P^2 = a^3 / M_{\text{total}}$$

# An application of the revised Kepler 3<sup>rd</sup> Law:

Find the mass of Jupiter using the orbital parameters of one of its satellites

- We want to obtain the mass of Jupiter using the mean distance (**a**) of one of its moon ( for example Io) and its orbital period (**P**)

$$\blacksquare M_{\text{total}} = M_{\text{Jupiter}} + M_{\text{Io}}$$

- But the mass of Io is much smaller than the mass of Jupiter (Jupiter has about 21,000 times more mass than Io)



The mass of Io can be neglected

- If we express **a** in AU and **P** in years, we can substitute the proportional sign for an equal sign

$$\blacksquare M_{\text{Jupiter}} = a^3 / P^2$$

- The mass of Jupiter will be given in **solar mass**
- **Another interesting application** : The equation allows to compute the mass of the black hole located at the center of the Milky Way . Using the mean distance and the orbital period of a star (or several stars) orbiting the black hole