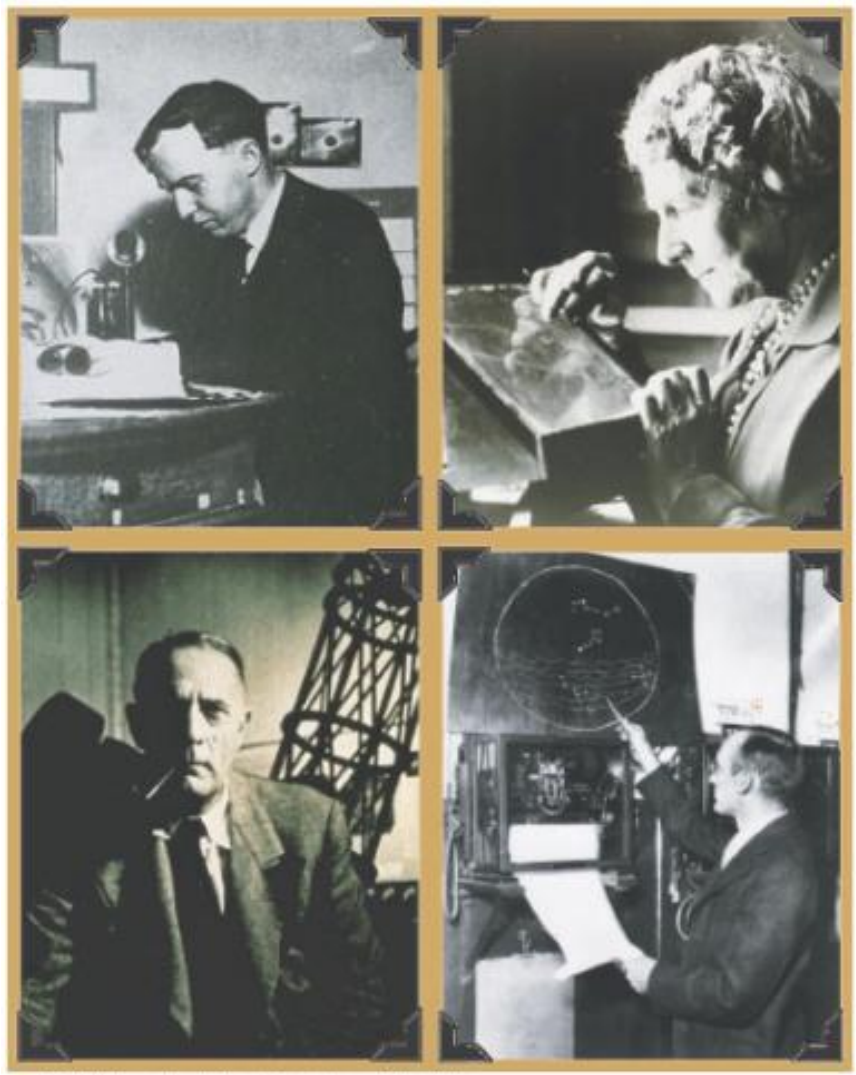
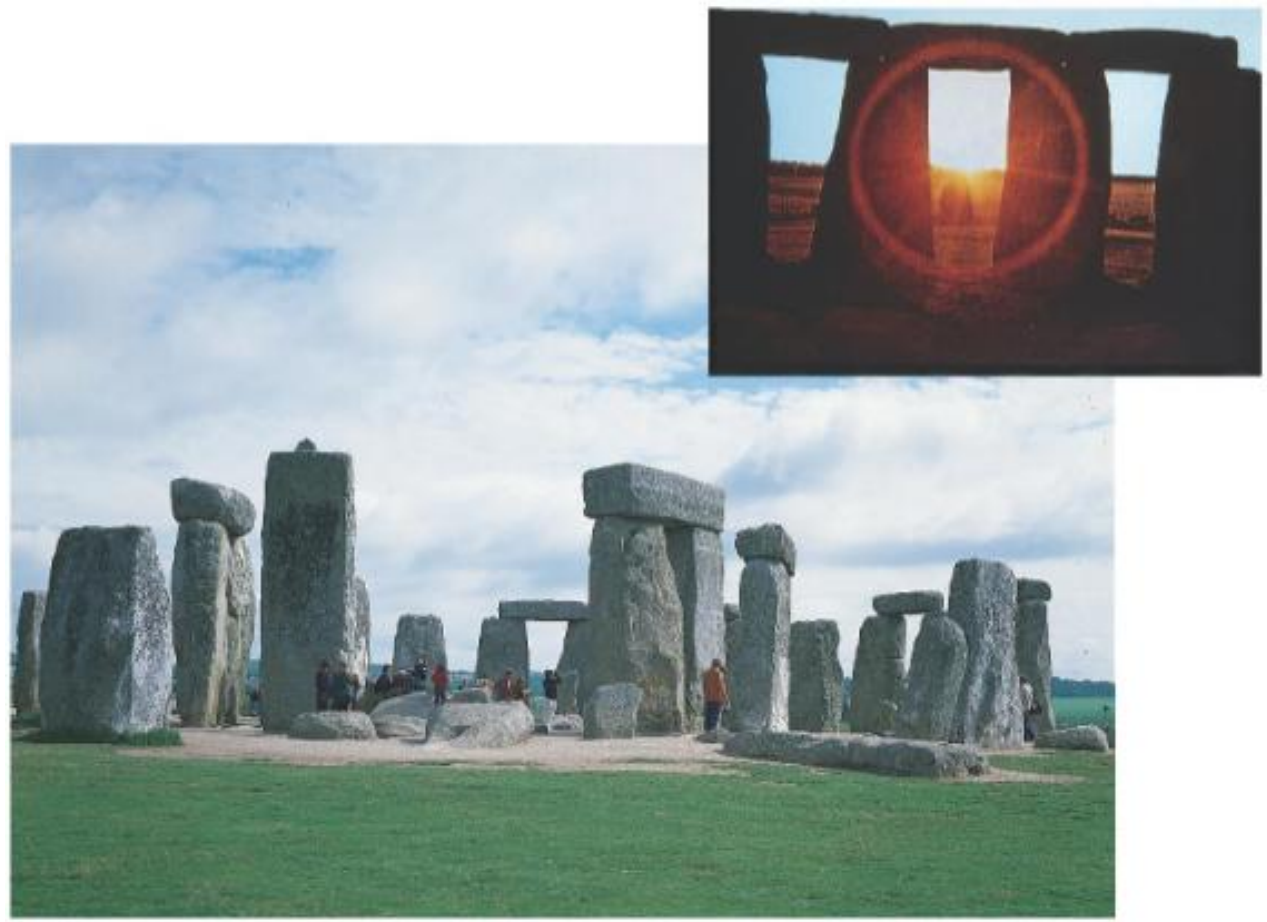
The Copernican Revolution



2.1 Ancient Astronomy

- Ancient civilizations observed the skies
- Many built structures to mark astronomical events

Summer solstice sunrise at Stonehenge:



2.1 Ancient Astronomy

Spokes of the **Big Horn Medicine Wheel** are aligned with rising and setting of Sun and other stars

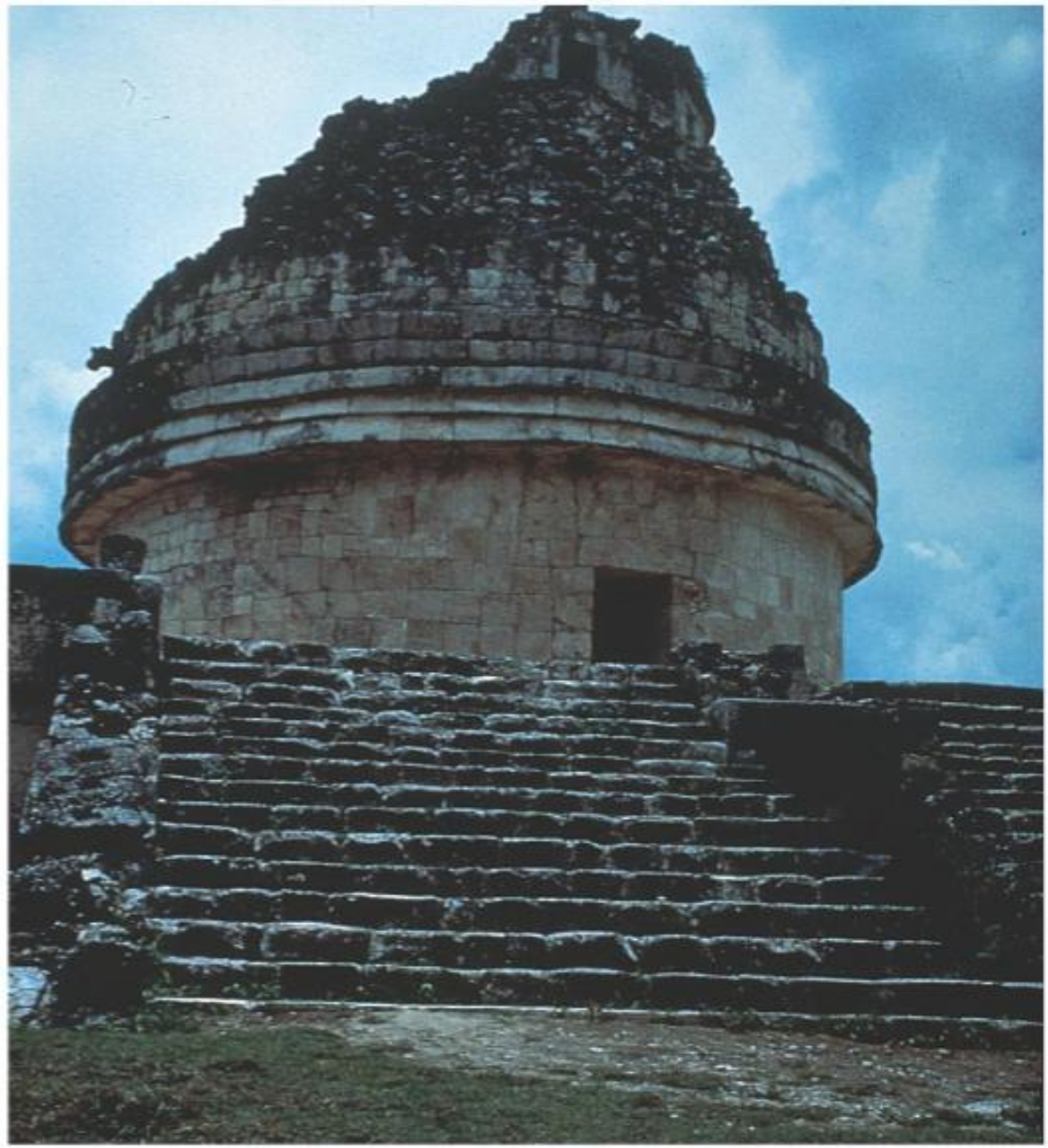
(a) Big Horn Mountains, Wyoming

2.1 Archeaoastronomy

Pre-Greek civilizations largely used astronomy & astrology for **religious**, **cultural**, or **agricultural** reasons.

History of Astronomy (pre-Greek):

- Mayan Calendar
- Egyptian Pyramids
- Chinese 'Mansions'
- Indian Vedic Astro

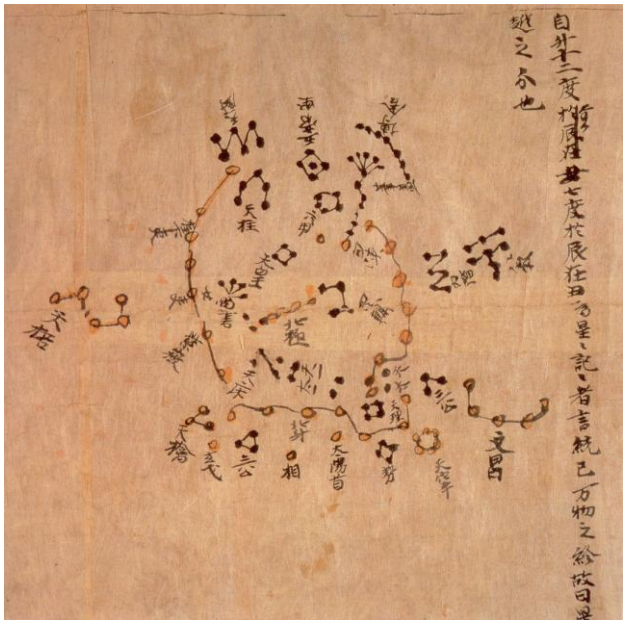


(b)

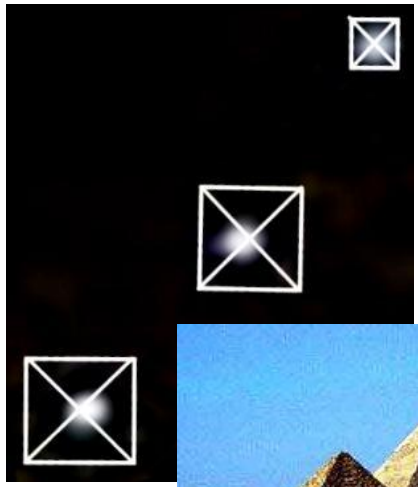
Ancient Cultures & Astronomy

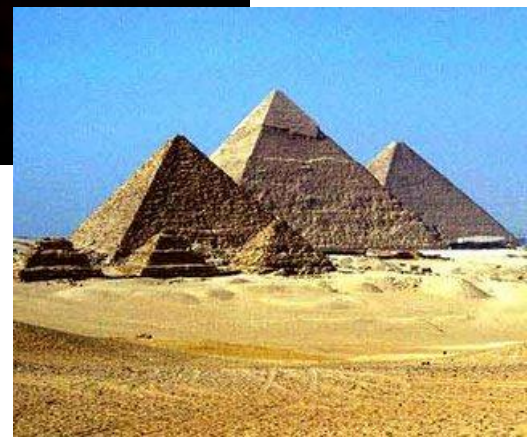
History of Astronomy (pre-Greek):

- Mayan Calendar
- Egyptian Pyramids
- Chinese 'Mansions'
- Indian Vedic Astro



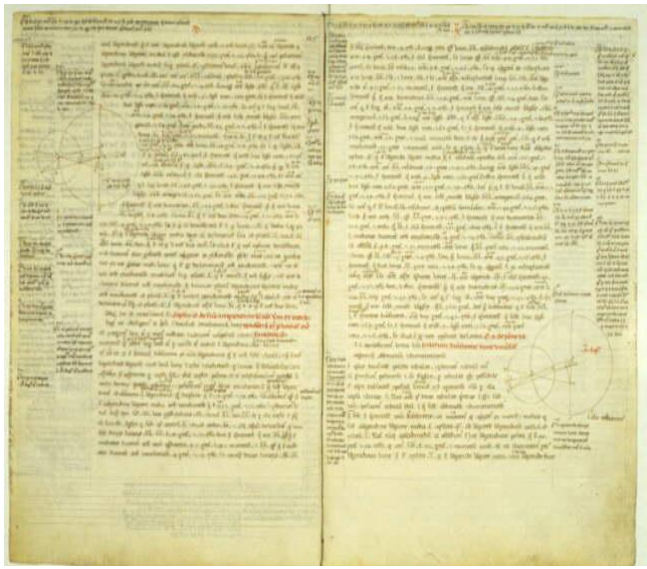
Chinese astronomers were excellent observers



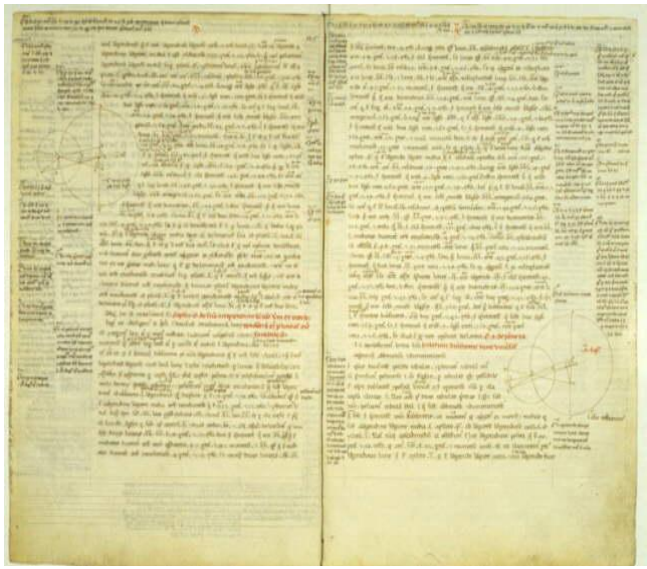


Greek & Islamic Astronomy

- Greek astronomy was built upon Babylonian astronomy.
- Hipparchus started Greek tradition of accurate astronomical predictions & wrote the 1st great star atlas.
- Aristarchus first introduced the idea of a heliocentric universe although other Greeks disagreed.
- Ptolemy is responsible for the great star atlas known as the Almagest on which Islamic astronomy was built. He promoted a geocentric universe.



Greek & Islamic Astronomy



- Islamic astronomy grew from the need to have an accurate calendar mainly for religious reasons.
- Many modern star names are Arabic words. Some were from the Almagest but many are not.
- Islamic astronomy was a ***scientific*** mindset and not ***astrological***.

2.2 The Geocentric Universe

Ancient astronomers observed:

Sun
Moon
Stars

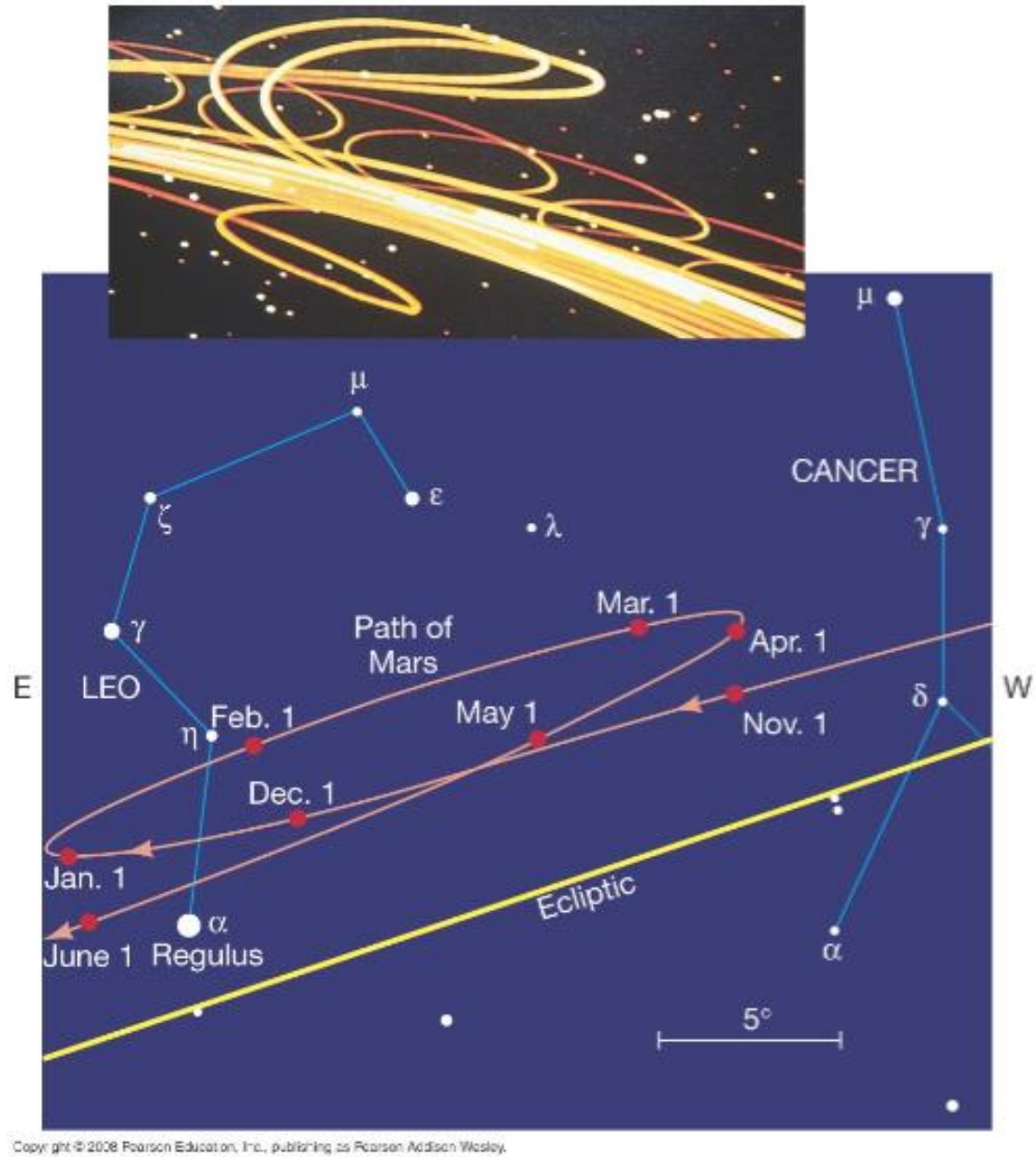
Five planets: Mercury, Venus, Mars, Jupiter, Saturn

2.2 The Geocentric Universe

Sun, Moon, and stars all have simple movements in the sky

Planets:

- Move with respect to fixed background of stars
- Change in brightness
- Change speed
- Undergo retrograde motion: observed motion is backwards, from E to W.
- Prograde: observed motion across the sky is from W to E



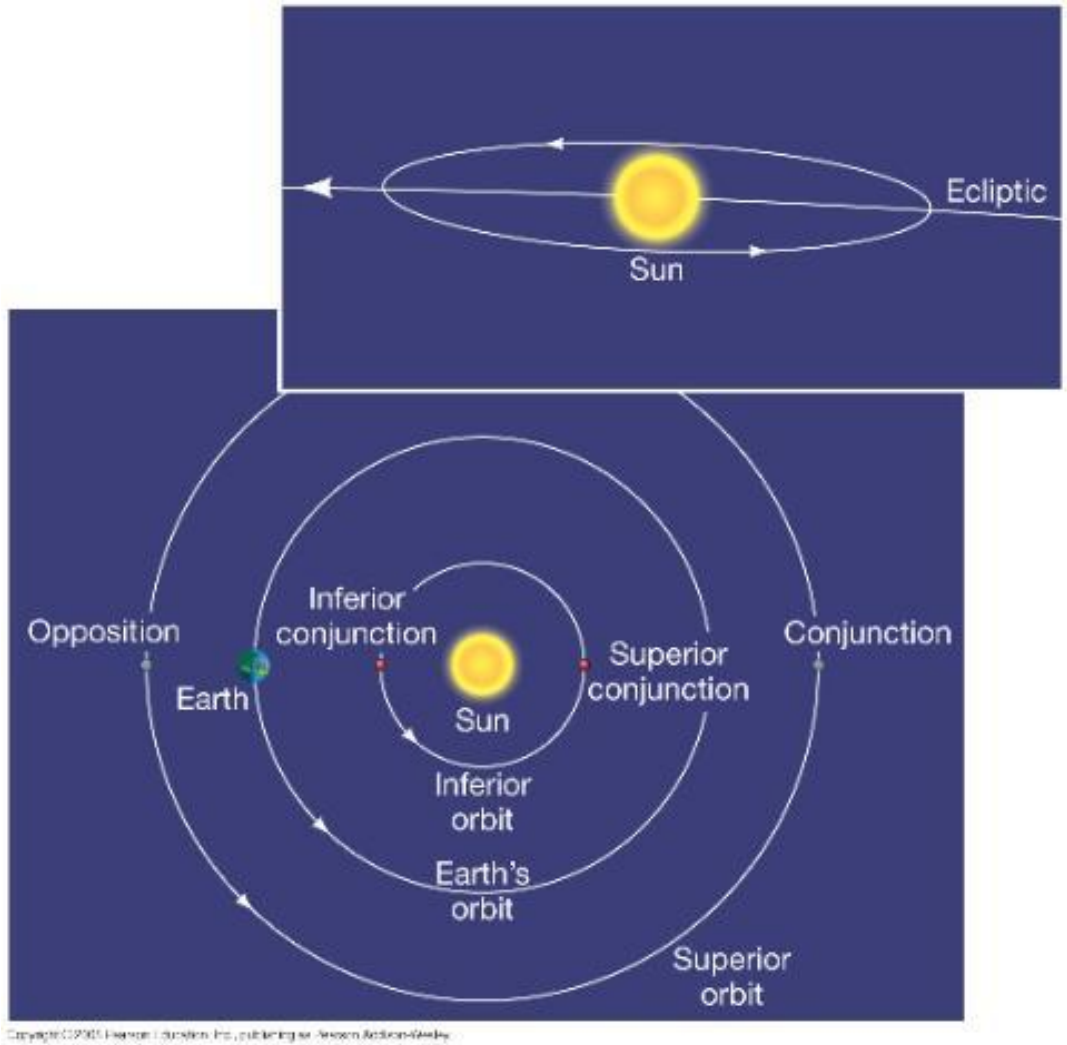
2.2 The Geocentric Universe

- 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



Planetary Configurations

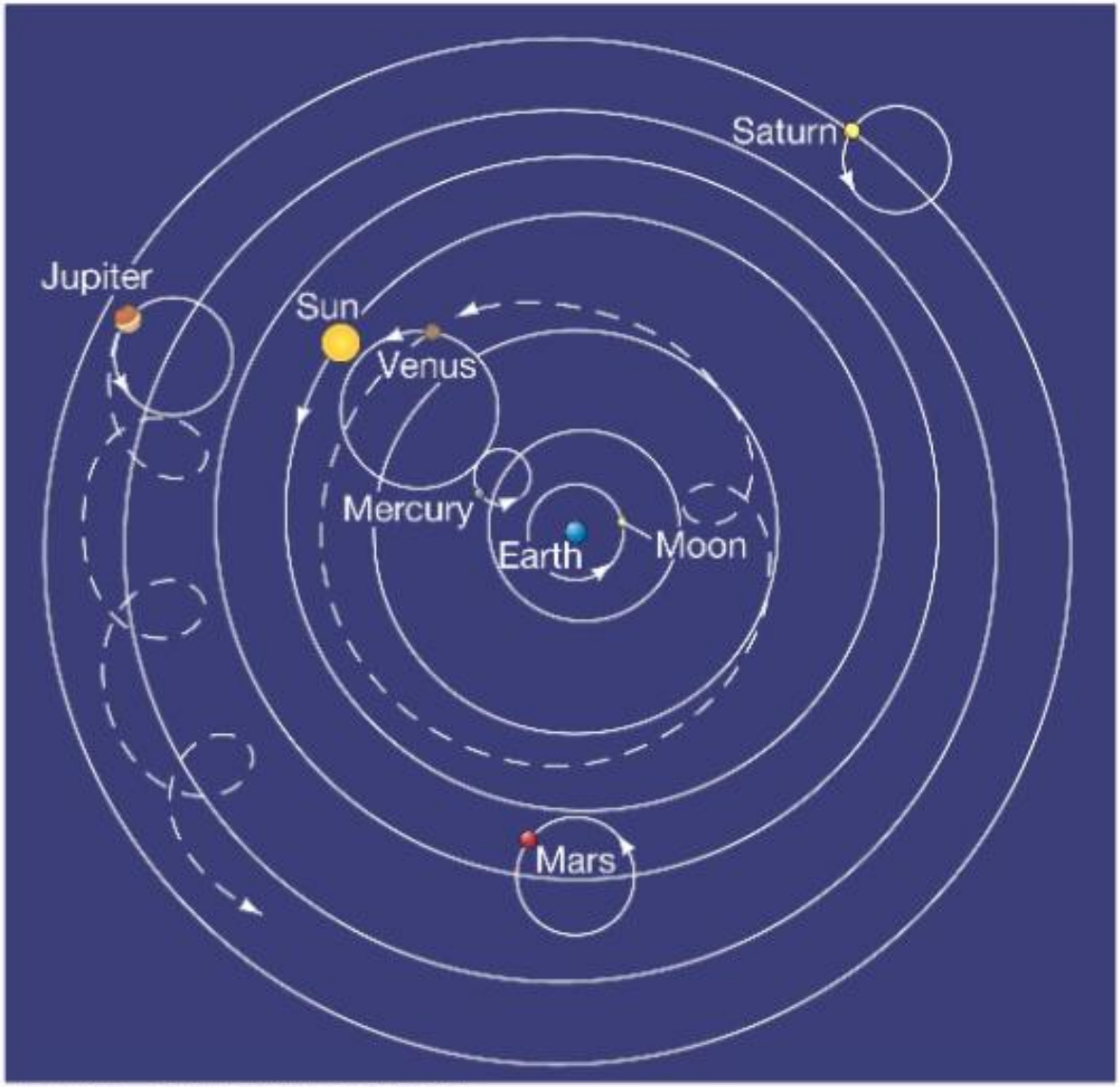
2.2 The Geocentric Universe

Early observations:

- **Inferior planets never too far from Sun**
- **Superior planets not tied to Sun; exhibit retrograde motion**
- **Superior planets brightest at opposition (two celestial bodies appear in opposite directions in the sky)**
- **Inferior planets brightest near inferior conjunction (same line as sun)**

2.2 The Geocentric Universe

Earliest models had **Earth** at center of solar system



2.2 The Geocentric Universe

Aristotle's Model: 350BC

- **As simple as it gets: Earth at center, everything orbits the earth on simple circular paths**
- **Supported by casual naked-eye observations**
- **Aristotle had sophisticated parallax argument for stationary earth**
- **Disadvantage: Cannot explain retrograde motion**

2.2 The Geocentric Universe

Aristarchus' Model: 300BC

- Aristarchus correctly put sun at center, planets (including Earth) in orbits around sun
- Aristotelian model wins because Aristotle has a stronger reputation and Aristarchus cannot solve the parallax problem

2.2 The Geocentric Universe

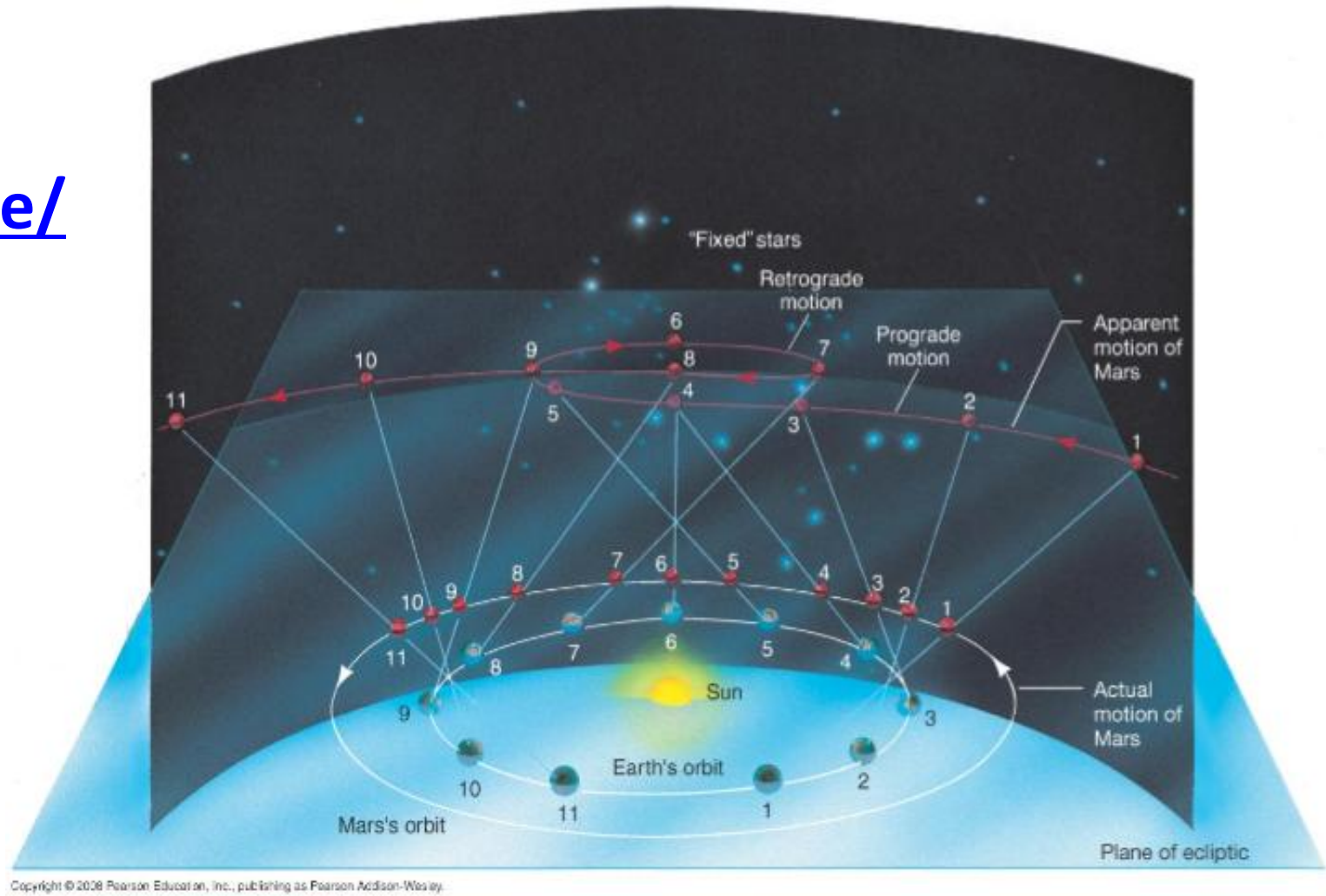
Ptolemy's Model: 140AD

- **Refines the Aristotelian model, but keep stationary earth at center**
- **Deferent: Main circle of planet's path around the earth**
- **Epicycle: Smaller circle on top of deferent**
- **Advantage: Epicycles on deferents can explain retro-grade motion**
- **Disadvantage: Increasingly inelegant, needs a crazy number of tweaks to make it agree with the increasing volume of observational data**

2.3 The Heliocentric Model of the Solar System

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

This figure shows https://youtu.be/72FrZz_zJFU



2.3 The Heliocentric Model of the Solar System

Copernicus:

- **Liked the simplicity and elegance of a sun-centered solar system**
- **Wrote a book about it, but was afraid to publish (with good reason)**
- **Allowed it to be published as he literally lay dying, but with a preface that essentially denied the contents**
- **All of Europe yawned...and ignored the book for a good 50 years**

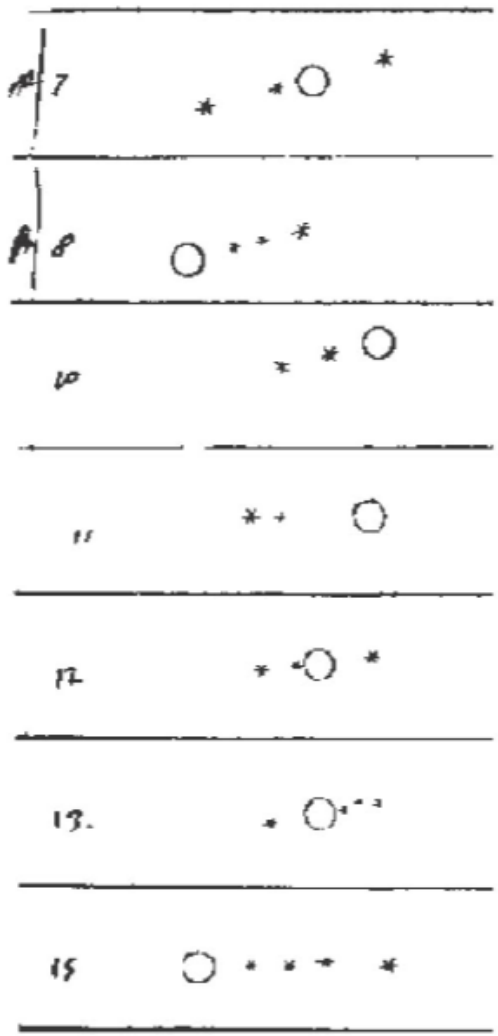
The Foundations of the Copernican Revolution

1. Earth is not at the center of everything.
2. Center of earth is 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 Modern Astronomy

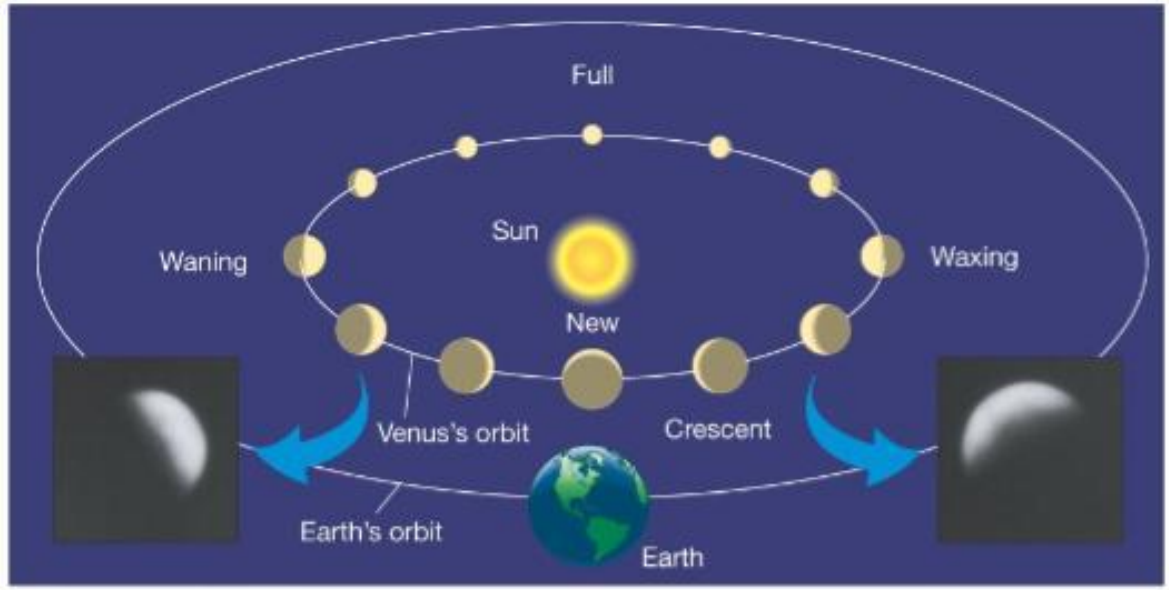
Telescope **invented around 1600**
Galileo **built his own, made observations:**

- **Moon has mountains and valleys:**
  - Craters and mountains mean that that the moon is not a perfect, smooth spherical celestial body
- **Sun has sunspots, and rotates:**
  - The sun is rotating, and it is not a perfect, smooth unblemished celestial body
- **Jupiter has moons (shown):**
  - Not everything orbits the earth
- **Venus has phases:**
  - full cycle of phases means that Venus cannot be in between the earth and the sun all the time

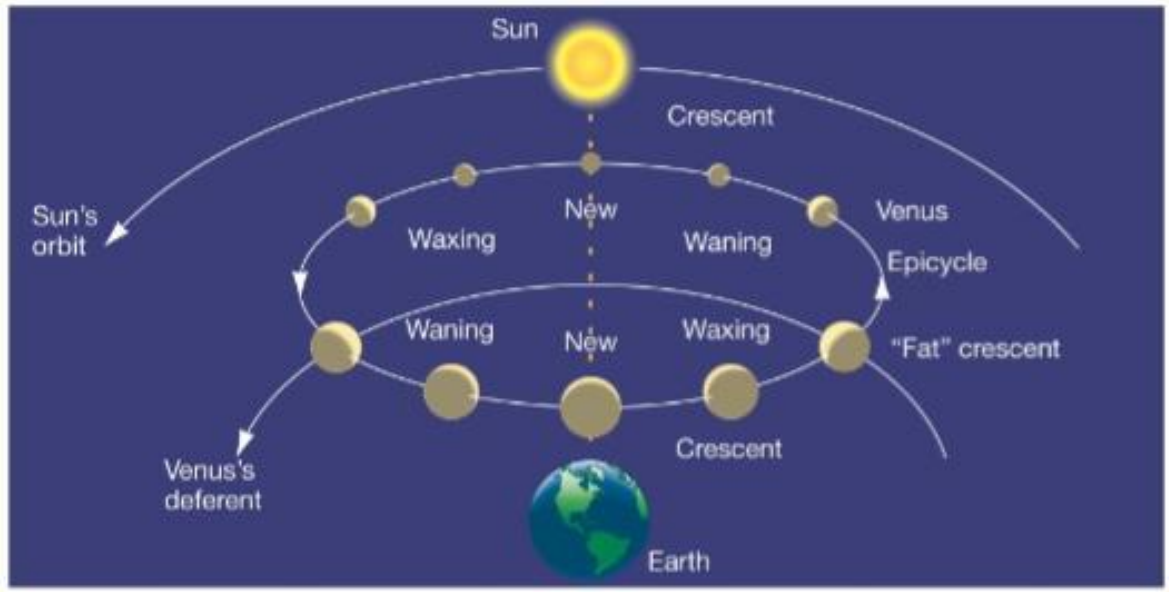


2.4 The Birth of Modern Astronomy

Phases of Venus cannot be explained by geocentric model without epicycles and Venus being tied to the sun's motion



(a) Sun-centered model



(b) Ptolemy's model

2.5 The Laws of Planetary Motion

Tycho Brahe:

- **Spent virtually every night of his adult life making astronomical observations**
- **Made his own instruments (very carefully and very accurately)**
- **Believed that the planets circled the sun, but the sun circled the stationary earth: sort of a hybrid of geo- and heliocentric models**

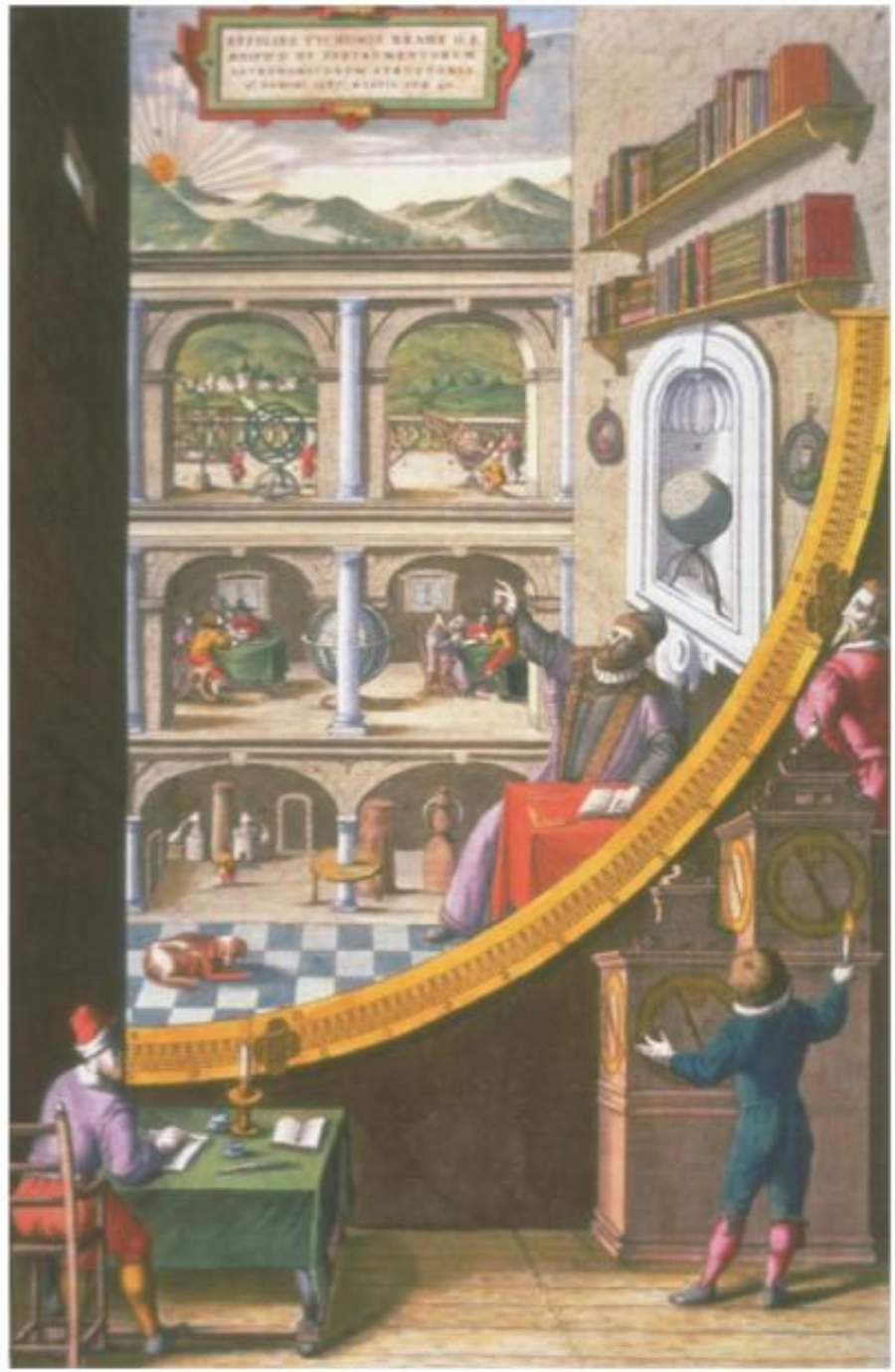
2.5 The Laws of Planetary Motion

Johannes Kepler:

- **Excellent mathematician**
- **Inherited Tycho's data, spent 30 years working it over**
- **Derived laws using observations made by Tycho Brahe**

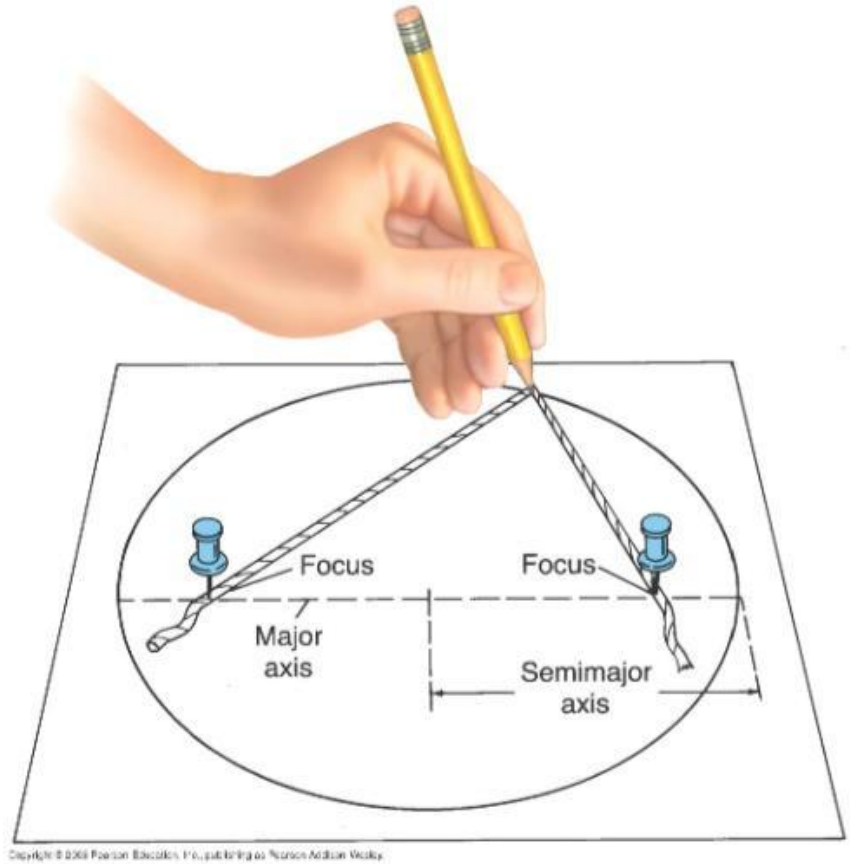
https://www.youtube.com/watch?v=6TGCPXhMLtU

Kepler's 3 Laws:
Planetary Orbit Simulator



2.5 The Laws of Planetary Motion

1. **Planetary orbits are ellipses, Sun at one focus**

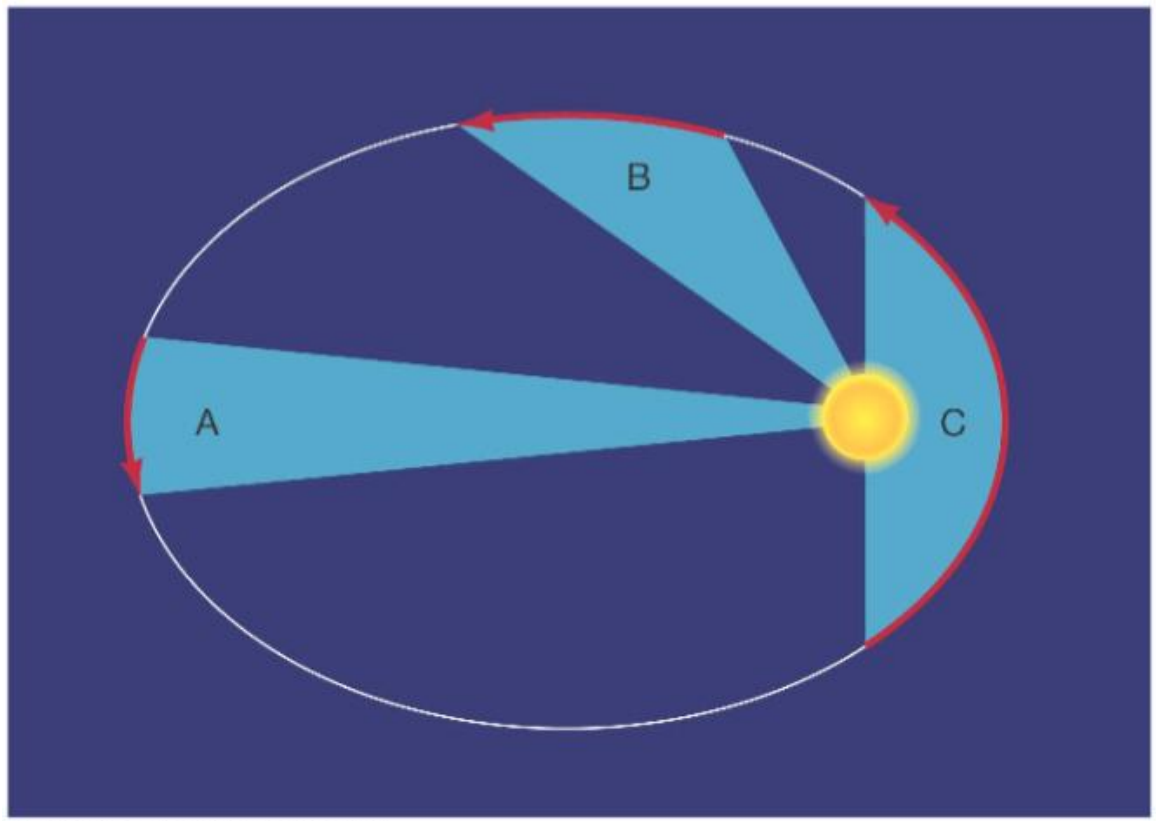


2.5 The Laws of Planetary Motion

2. Imaginary line connecting Sun and planet sweeps out **equal areas** in **equal times**

-This means that closer = faster: Orbital speed ≠ constant

- Perihelion: When a planet gets closer to the sun, it speeds up
- Aphelion: As a planet moves farther away from the sun, it slows down



2.5 The Laws of Planetary Motion

3. Square of **period** of planet's orbital motion is proportional to cube of **semimajor axis**

- ($P^2 = a^3$)
- A planet closer to the sun will complete one orbit in less time than a planet farther from the sun (This means that closer = faster)

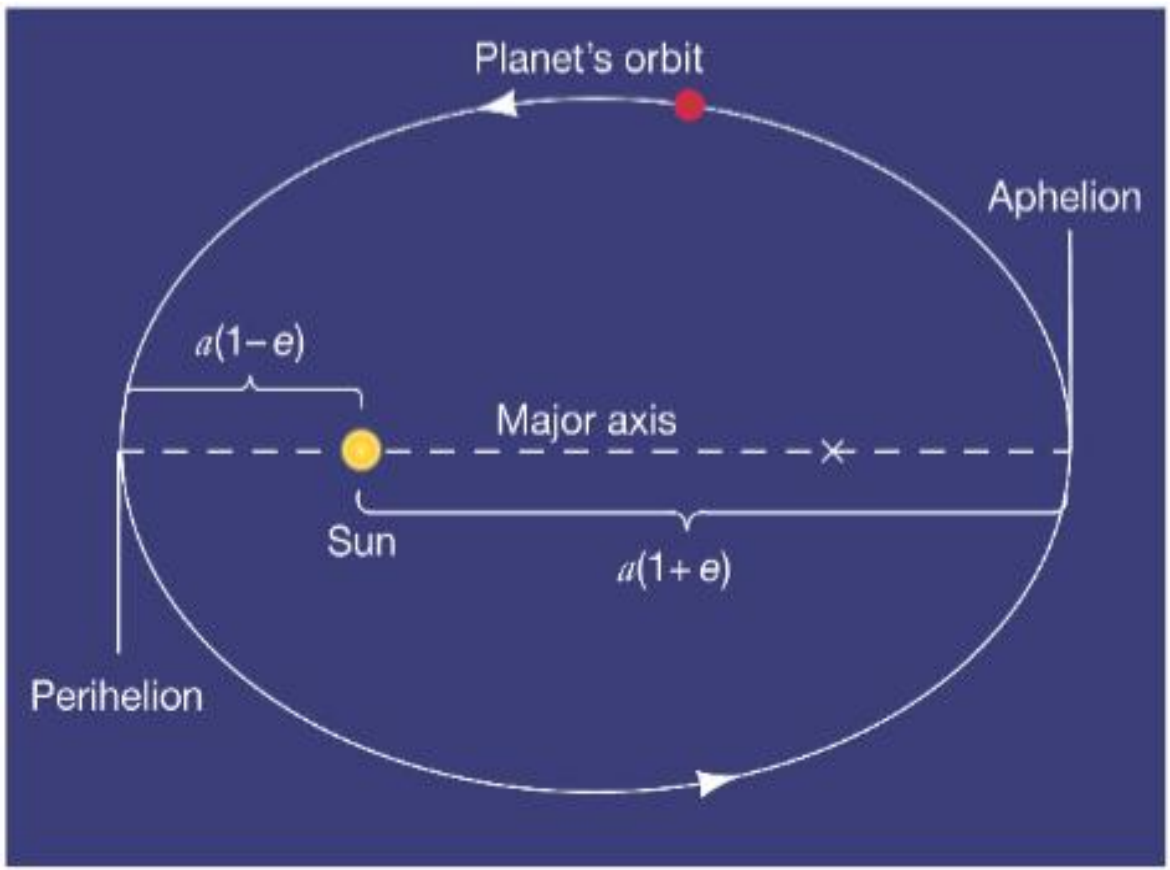
TABLE 2.1 Some Solar System Dimensions

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

- Embed Kepler's Laws Video Here…

More Precisely 2-1: Some Properties of Planetary Orbits

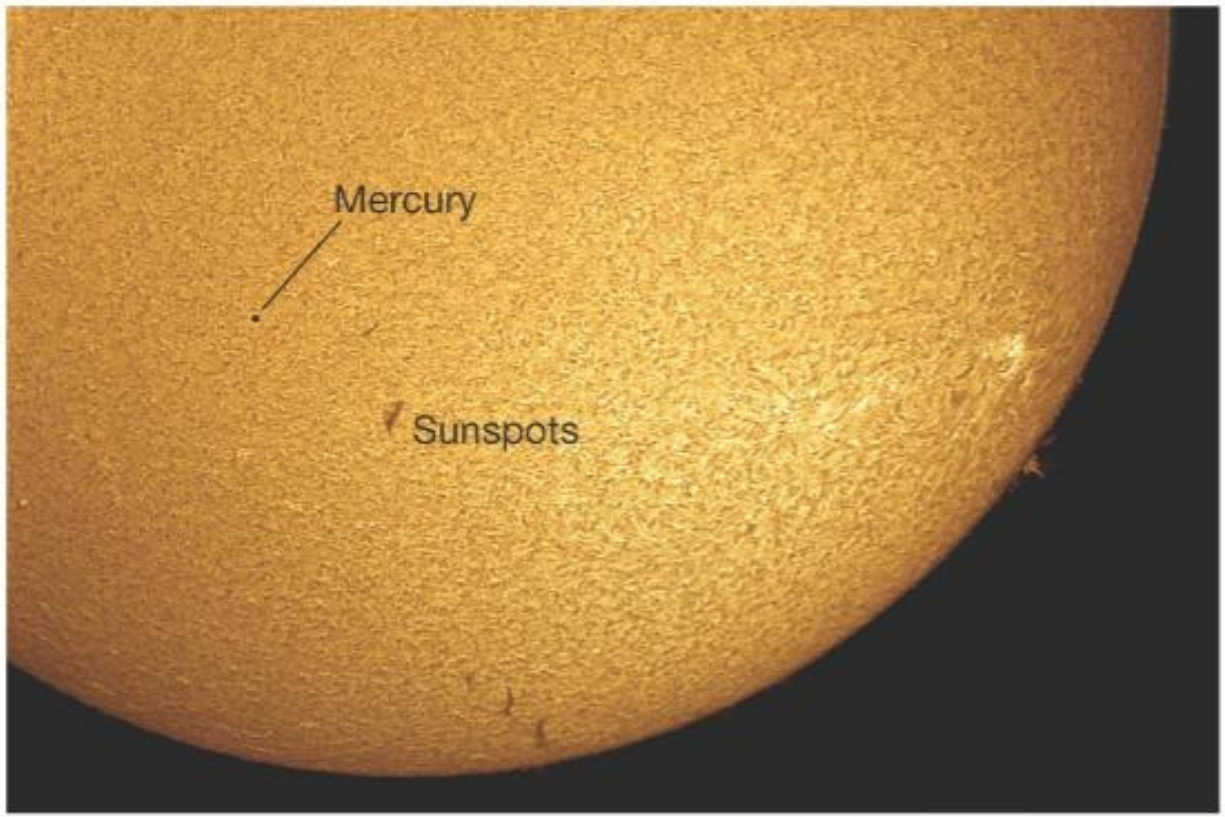
Semimajor axis and eccentricity of orbit completely describe it
Perihelion: closest approach to Sun
Aphelion: farthest distance from Sun



2.6 The Dimensions of the Solar System

Astronomical unit: mean distance from Earth to Sun

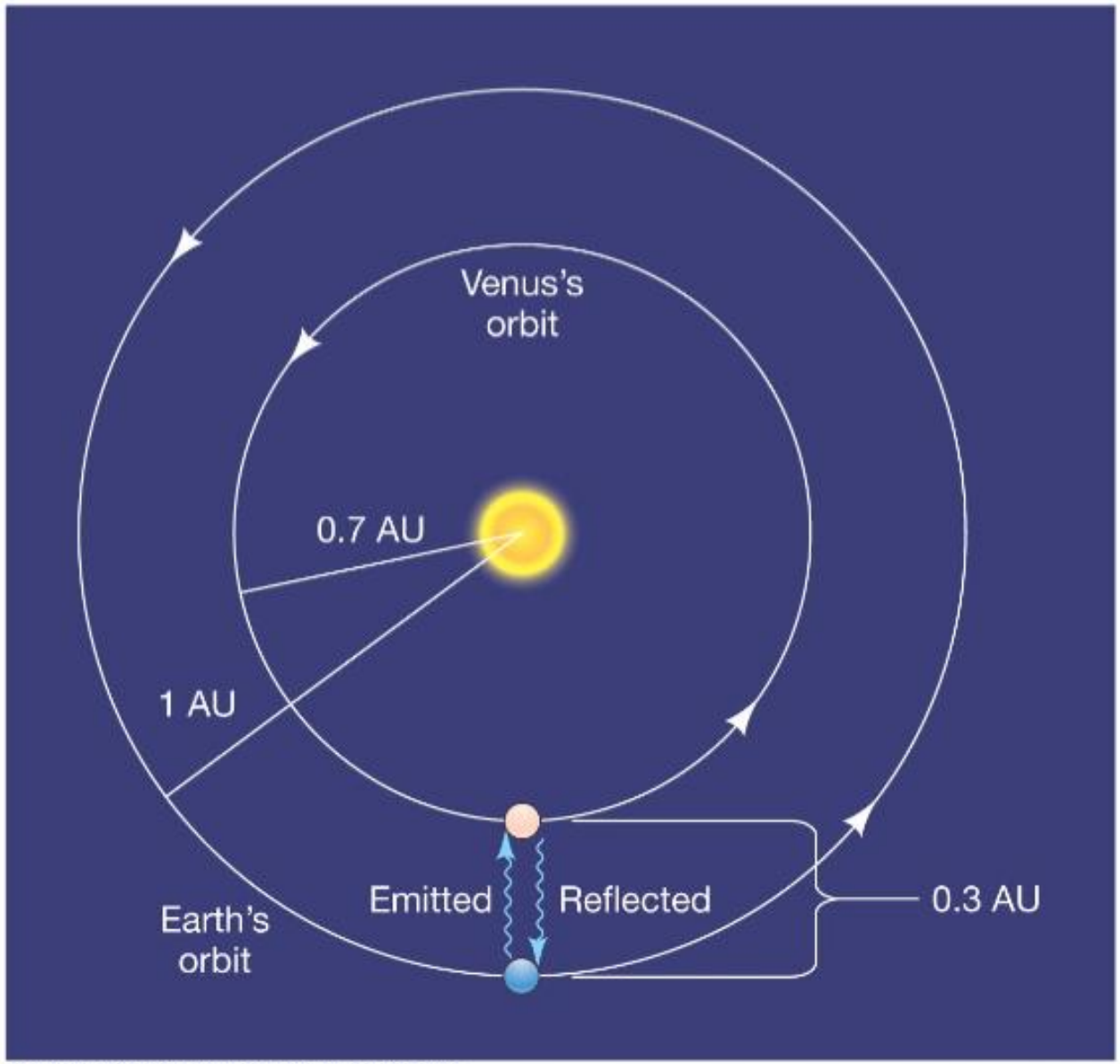
First measured during transits of Mercury and Venus, using triangulation



2.6 The Dimensions of the Solar System

Now measured using **radar**:

Ratio of mean radius of Venus' orbit to that of Earth very well known



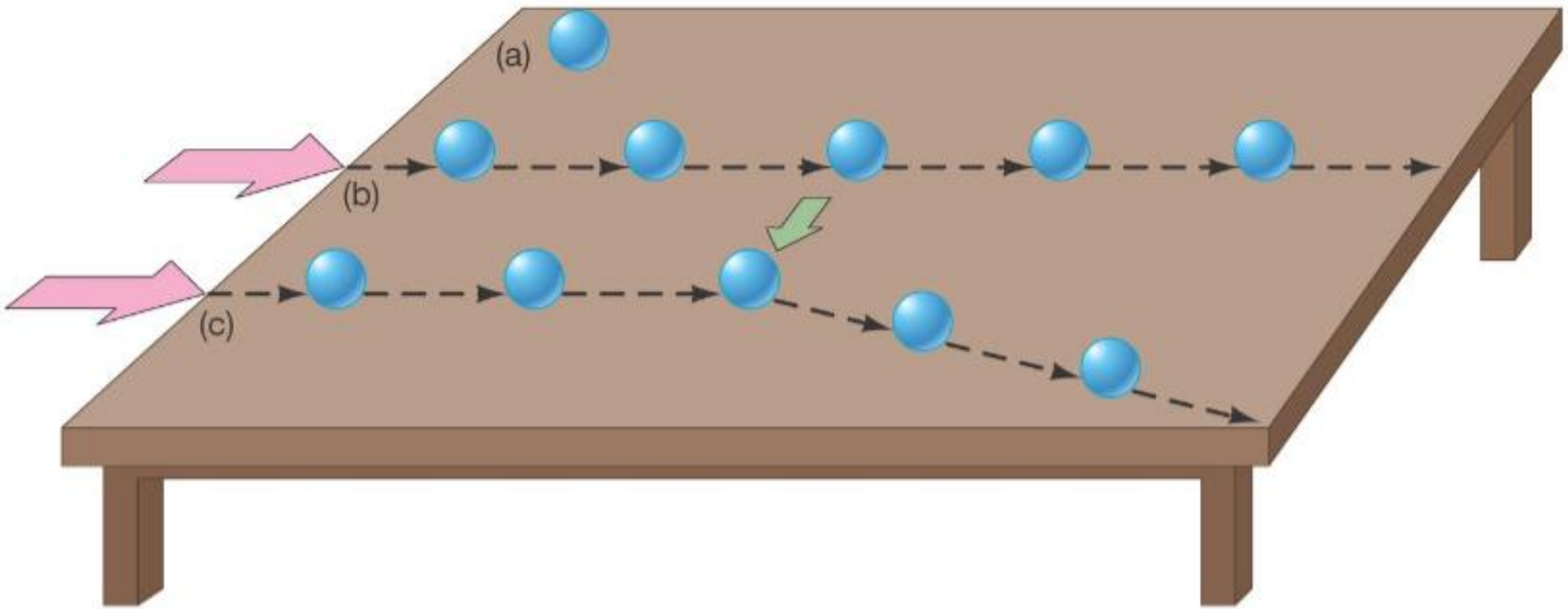
2.7 Newton's Laws

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

2.7 Newton's Laws

Newton's First Law:

An object at rest will remain at rest, and an object moving in a straight line at constant speed will not change its motion, unless an external force acts on it.



2.7 Newton's Laws

Newton's First Law:

Inertia = object's resistance to change in motion

Mass measures inertia: More mass means more inertia

Object (whatever it is) wants to continue doing what it is doing (at rest or in motion)

Force is required to change the state of motion of an object

2.7 Newton's Laws

Newton's second law:

When a force is exerted on an object, its acceleration is inversely proportional to its mass:

$$F = ma$$

- **Acceleration = change in motion (speed or direction)**

- **More force, more acceleration**

- **Apply the same amount of force: Less mass, more acc (more mass, less acc)**

2.7 Newton's Laws

Newton's third law:

When object A exerts a force on object B, object B exerts an equal and opposite force on object A.

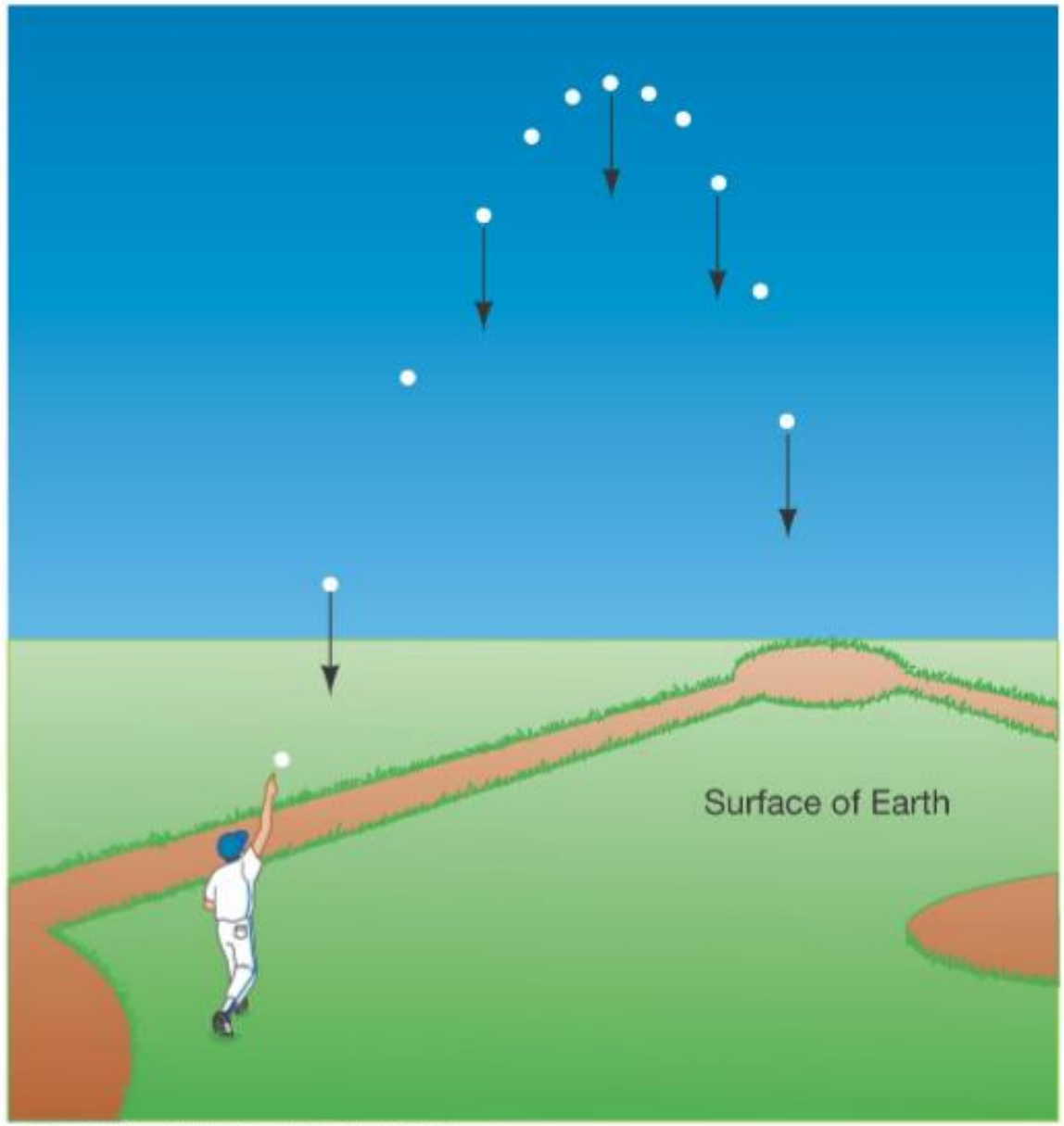
- **Forces come in pairs**

- **Force pairs act on two different objects (force on ball because of bat, force on bat because of ball)**

2.7 Newton's Laws

Gravity

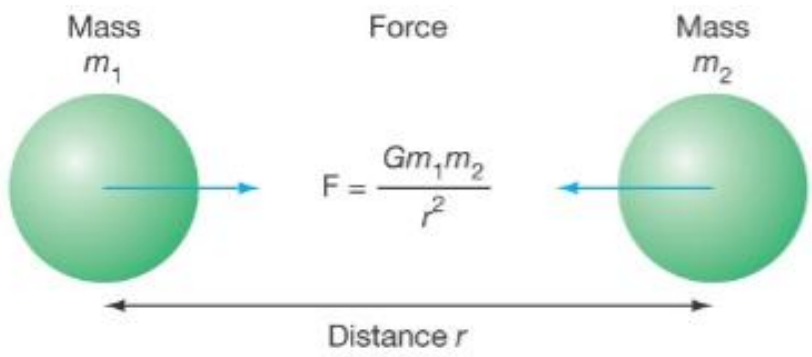
On the Earth's surface, acceleration of gravity is approximately constant, and directed toward the center of Earth



2.7 Newton's Laws

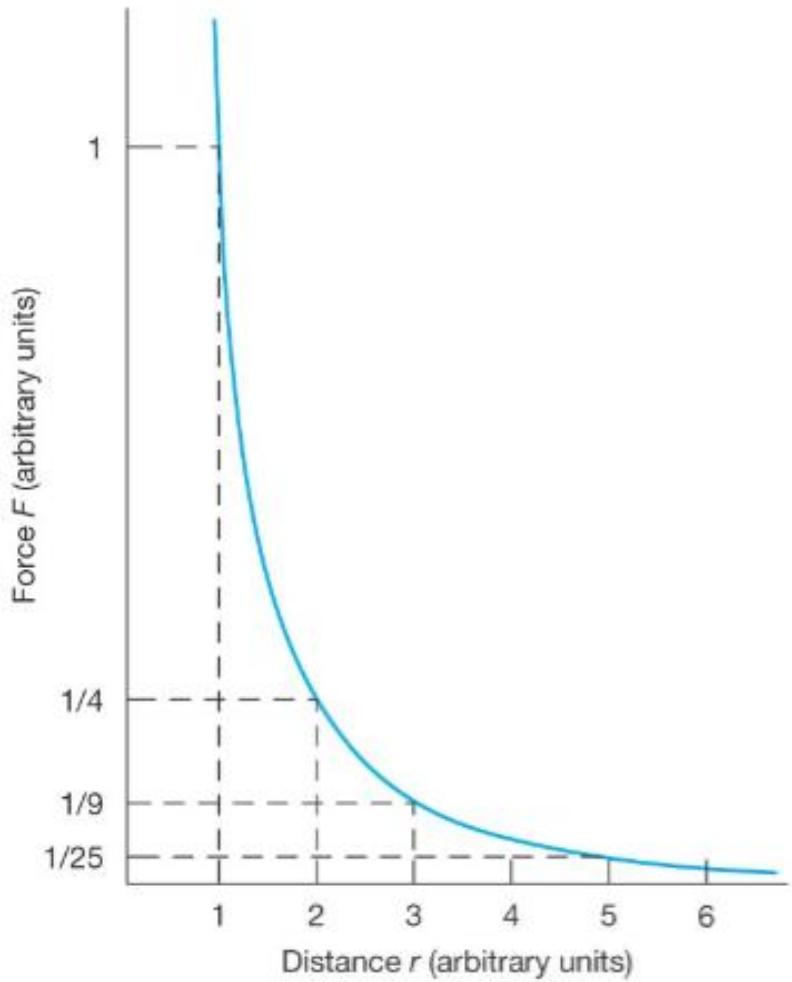
Gravity

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



- **Every mass is attracted to every other mass in the universe**

- **Force of gravity is always attractive (pulls masses toward each other)**



2.7 Newton's Laws

Gravity

$$F = \frac{Gm_1m_2}{r^2}$$

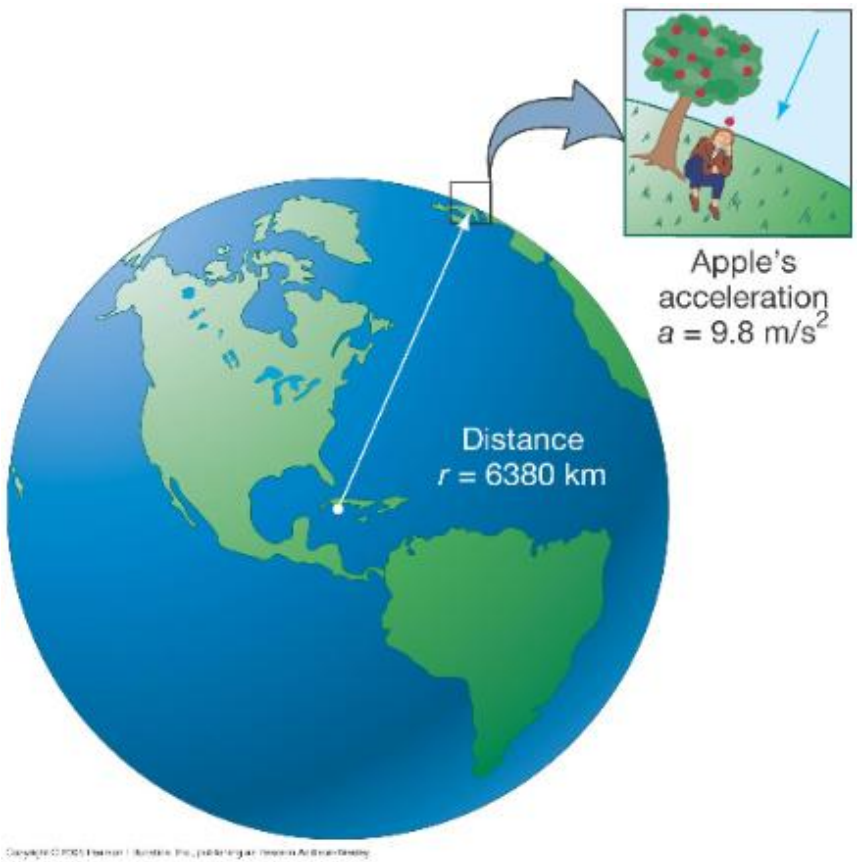
The constant *G* is called the gravitational constant; it is measured experimentally and found to be:

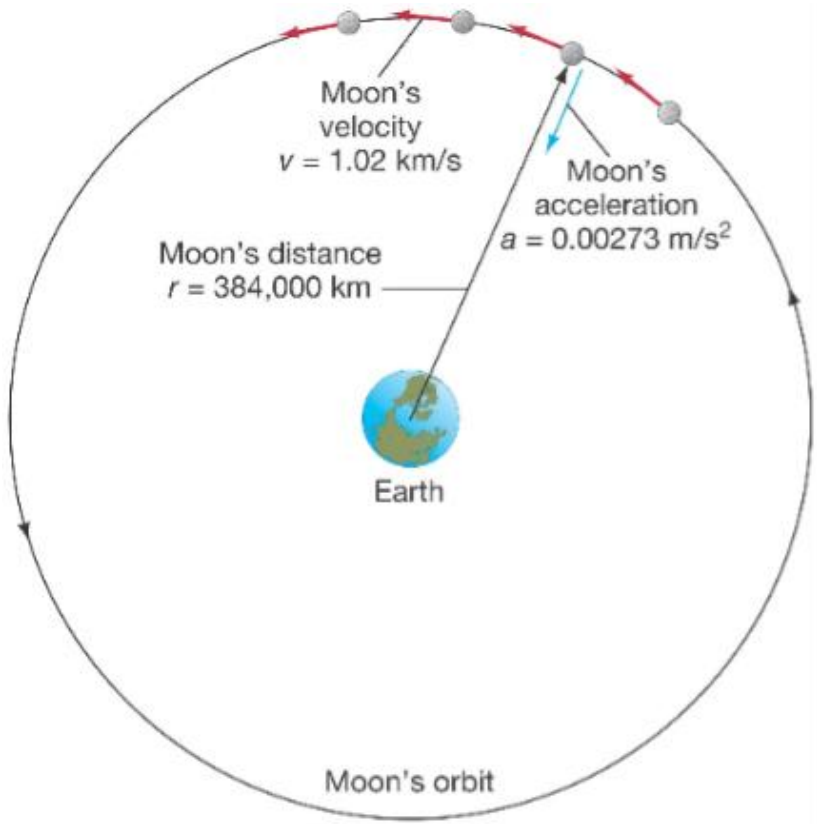
$$G = 6.67 \times 10^{-11} \text{ N m}^2/\text{kg}^2$$

More Precisely 2-2: The Moon is Falling!

Newton's insight: same force causes apple to fall and keeps Moon in orbit; decreases as square of distance, as does centripetal acceleration: $a = v^2/r$

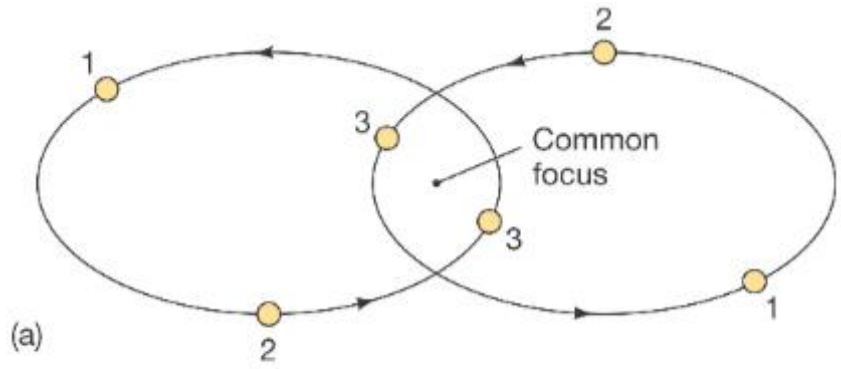
Orbits are not possible without gravity



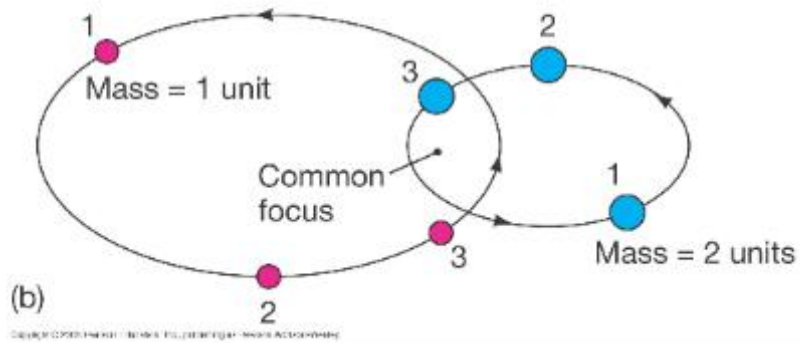


2.8 Newtonian Mechanics

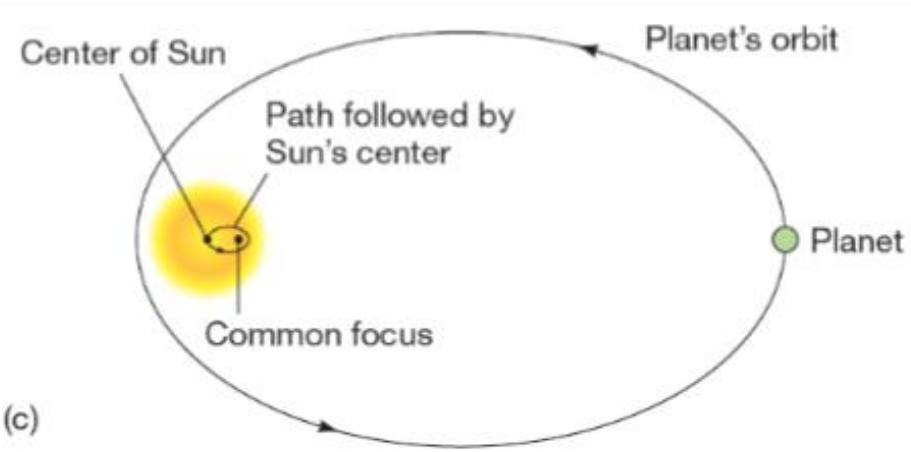
Kepler's laws are a consequence of Newton's laws;



-Newton's Laws explained WHY objects move
-Kepler's Laws describe HOW they move



Kepler's 1st law needs to be modified:
The orbit of a planet around the Sun is an ellipse, with the center of mass of the planet–Sun system at one focus.



More Precisely 2-3: 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 x 10^{30} kg (!)

2.8 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.