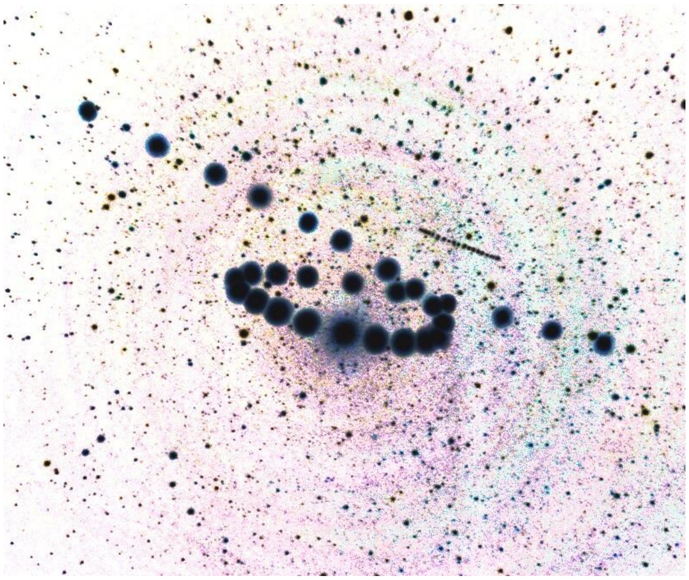
Chapter 2: Gravitation and the Waltz of the Planets

Models of the Solar System: Geocentric Model of the Solar System

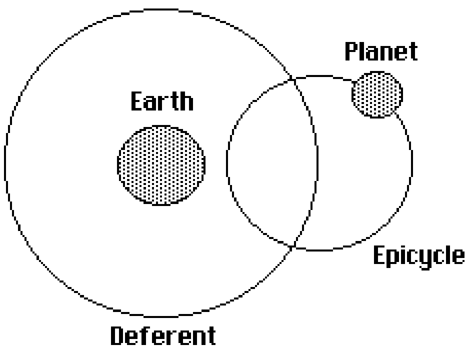
1. Earth centered. The Greek philosopher Aristotle (350 BC) proposed that if the Sun were at the center of the universe stellar parallax would be observed. Since his assumption that the stars were relatively near by was wrong, they did not observe any stellar parallaxes. Therefore, Aristotle came to the conclusion that the Earth was at the center.

2. Circular orbits. Considered circles to be perfect geometrical shapes.

3. Explanation of retrograde motions (Mars, Jupiter, and Saturn) and motions of Venus and Mercury provided by using epicycles placed on the orbits of the planets (perfected by Ptolemy).



Retrograde Loop of Mars in 2003



4. Over time it was a poor predictor of planetary positions.

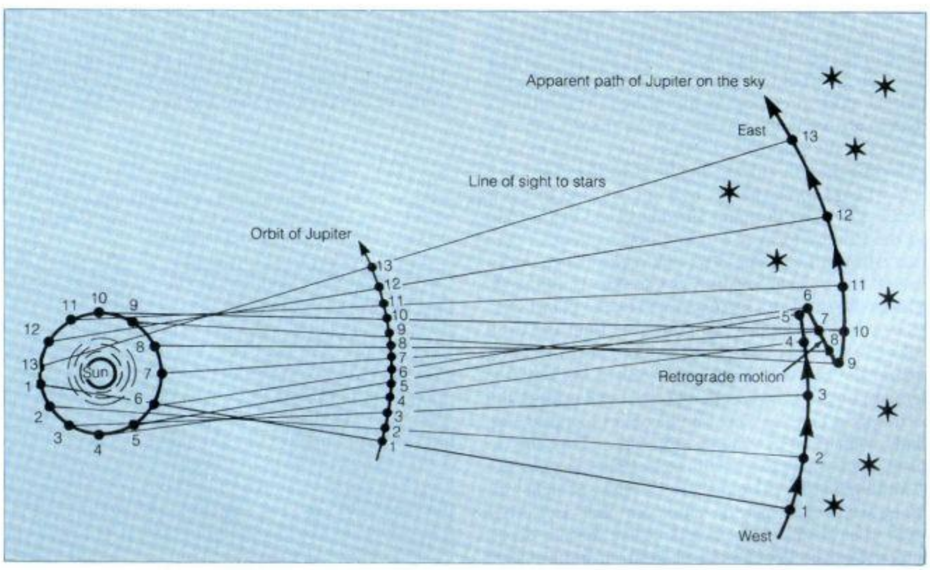
Other Greek Contributions:

1. Aristarchus (250 B.C.): Devised a way to measure the relative sizes and distances of the Moon and Sun.
2. Eratosthenes (200 B.C.): Measured the Earth's size by applying geometry to the shadows cast in wells at Aswan and Alexandia on the same date.
3. Hipparchus (130B.C.): Discovered precession by comparing the star maps of the Babylonians with the star map that he compiled. He noticed unusual shifts in the north celestial pole, vernal, and autumnal equinoxes, as well as other coordinates.

Heliocentric Model:

Copernicus: proposed a Sun centered model with circular orbits. Model was no better than the geocentric model at predicting long term positions of planets. However, it provided a simpler explanation for retrograde motion.

FIG. 1.21. RETROGRADE MOTION. As the faster-moving earth overtakes a superior planet in its orbit, the planet temporarily appears to move backward with respect to the fixed stars. This sketch illustrates the modern explanation of something that took ancient astronomers a long time to correctly understand.



Tycho Brahe: made accurate observations of planets using precise instruments (quadrants and cross-staffs). Also, he showed that the supernova of 1572 was very far away by not being able to measure any parallax.

Kepler: used Brahe's observations to deduce the correct shape of planetary orbits.

Kepler's Three Laws:

1. Orbits are ellipses with the Sun at one focus

2. Planets sweep out equal areas in equal time intervals.

3. $P^2 = A^3$ (P is measured in years and A is measured in AU)

Concept Test

Kepler's third law (that the period squared is proportional to the semi-major axis cubed) does NOT apply to the motion of

a) a satellite around the Earth.
b) a comet around the Sun.
c) a star around another star in a binary system.
d) one galaxy about another.
e) All of the above apply.

Galileo: made observations that supported the heliocentric model.

1. Observed phases of Venus. The gibbous phase of Venus is also smaller than the crescent phase, which could only be explained if Venus revolved around the Sun.

2. Moons of Jupiter. (Another center of motion.)

3. Sunspots. (Sun was not a perfect sphere.)

4. Craters and mountains on the Moon. (Moon was not a perfect sphere.)

5. Milky Way made of many stars. This was a contradiction to the idea that there could not be any more stars than what the eye could see.

Galileo is considered to be the father of experimental science. He was the first to apply the scientific method.

Newton: developed a universal theory to deal with planetary motion and motions on the Earth that can be applied anywhere in the universe.

Definitions:

1. Velocity: change in position during a change in time.

2. Acceleration: change in velocity during a change in time.

3. Mass: measure of the amount of matter in an object. Sometimes called the measure of inertia of an object.

Three Laws of Motion:

1. A body at rest will remain at rest and a body in motion will remain at a constant speed if no external forces are present.(Sometimes called the law of inertia.)

2. The total force on a body is equal to the product of its mass times its acceleration.

$$F = ma$$

3. For every force that a body exerts on a second body there is an equal and opposite force generated by the second body on the first. (For every action there is an equal and opposite reaction.)

Law of Gravitation: describes the gravitational force between two bodies.

$$F = \frac{GM_1M_2}{d^2}$$

Distance Change	Force Change
2	1/4
4	1/16
5	1/25
10	1/100

Inverse square law.

F – force of attraction
G – constant
M_1 – mass of larger body
M_2 – mass of smaller body
d – distance between the two bodies

Weight: a measure of the force of gravity on a body.

Weightlessness: describes the condition when an object does not experience any acceleration relative to its surroundings (ex. astronaut in a space capsule does not feel any acceleration relative to the capsule but gravity is still exerting a force on him.)

Concept Test

The time that it takes a small body to orbit about a large one depends only on

a) the mass of the small body.
b) the mass of the large body.
c) the radius of the orbit.
d) a and b.
e) b and c.

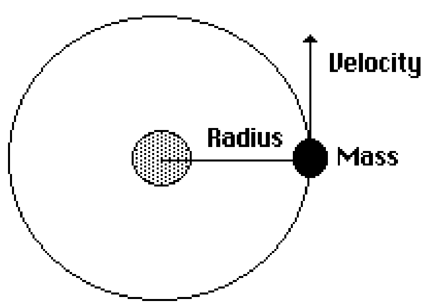
Momentum:

Linear Momentum: product of mass times velocity ($p = mv$).

Newton's 1st law: conservation of linear momentum.

Angular Momentum: planetary motion involves motion along a curved path. Think of angular momentum as the amount of rotation and revolution of an object.

Angular Momentum = Mass x Velocity x Radius (MVR)



Angular momentum is always conserved. If the radius decreases then the velocity must increase. The term conserved means that the total amount of angular momentum always remains the same.

Newton's Form of Kepler's 3rd Law:

$$(M_1 + M_2)P^2 = A^3$$

This can be used to determine the masses of stars and planets assuming that one of the masses is much smaller than the other or if there is a way to determine the ratio of the two masses (eclipsing binary stars - more later in the course). Here the period is measured in years, the semi-major axis in astronomical units, and the masses in solar units (multiples of the Sun's mass). This applies planets, stars, galaxies, ...
Newton also found that the orbits of comets could be parabolas or hyperbolas.

Successes of Newton's Theory:

1. Discovery of Neptune by Adams and Leverier using Newtonian physics.

2. Prediction by Edmund Halley of the return of the comet that bears his name.

Proof of the Heliocentric Theory:

1. Aberration of starlight: apparent shift of star positions due to earth's motion and the finite speed of light. During the course of a year a star's position

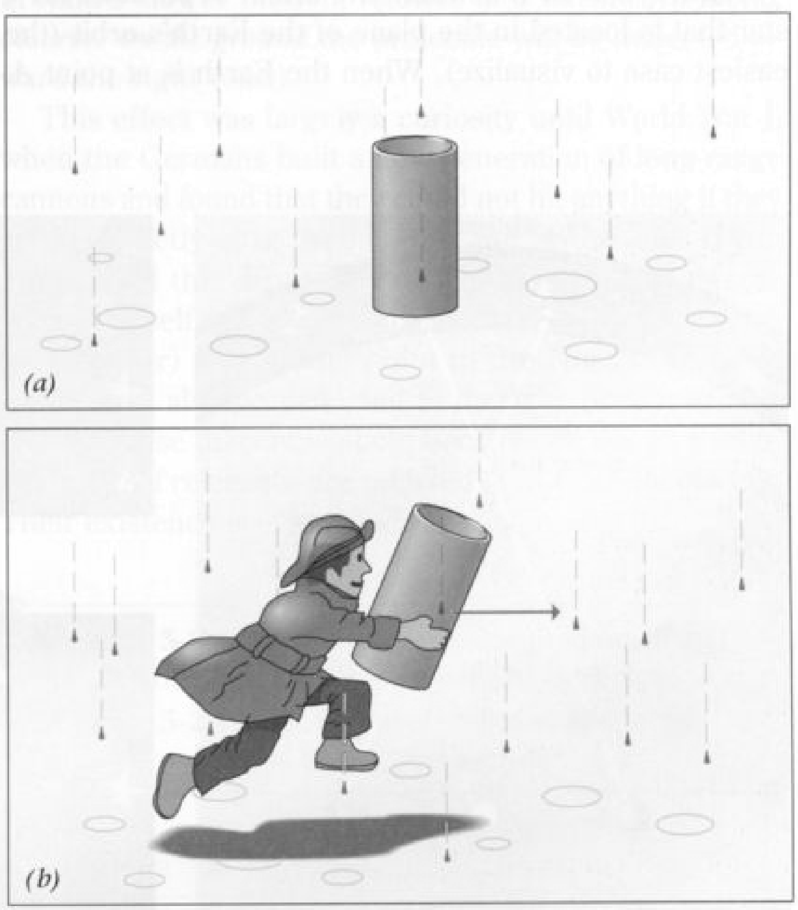
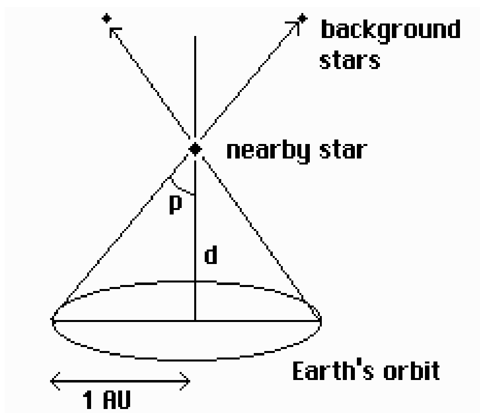


FIGURE 5-23. (*a*) A pipe in the rain. Raindrops fall straight to the bottom. (*b*) Moving a pipe in the rain. It must be tilted to keep the drops from hitting the side.

can deviate by as much as 20 seconds of arc on either side of its true position. This was discovered in 1729 by the British Astronomer Royal, who was trying to measure stellar parallax. Telescopes, during the 18th century, were accurate enough to measure this phenomena but not yet accurate enough to measure parallax.

2. Observation of stellar parallax: first proof that the Earth revolves about the Sun (see Essentials for Understanding III). Friedrich Bessel measured the first stellar parallax in 1838, by measuring the parallax of 61 Cygni (0.6").



Parallax allows the distances to stars to be determined.

Example: Proxima Centauri has p = 0.00021 degrees.

$$d= 57.3^{o}\ 1\ AU/\ 0.00021^{o} = 270{,}000\ AU$$

Evidence of Earth's Rotation:

1. Deflection of projectiles by the coriolis effect

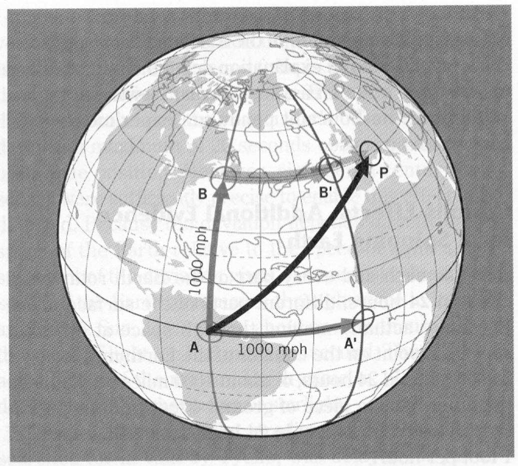


FIGURE 5-26. A cannonball fired northward from the equator (from A toward B) at 1000 mph is also moving eastward at 1000 mph (represented by the red arrow AA'), because this is the eastward speed of the cannon itself. The land over which the projectile travels moves more slowly than the equator. As a result, the projectile will arrive at P rather than B'. From the point of view of a north-facing gunner at A, the cannonball has been deflected to the right of the targeted location, landing at P rather than B'. Note that the length of BP is the same as AA'.

2. Wind circulation around low pressure centers.

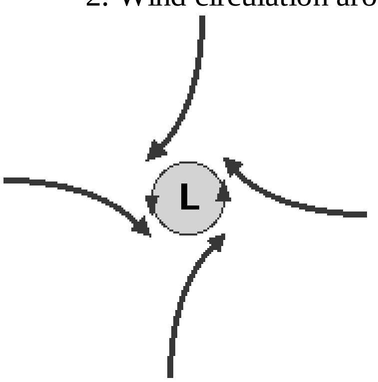
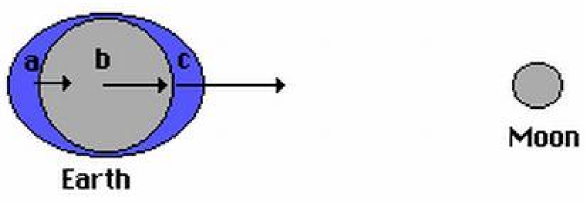


Figure 4: Vortex created in a low-pressure system.

3. Foucault Pendulum

Tides

Tides: produced by gravitational pull (differential gravitational force) of the Moon and Sun. Contribution of the Sun is only 1/2 as important as the Moon.



Gravitational force is greater at pt. c than pt. b, and greater at pt. b than at pt. a

Bulge at c is caused by the Moon pulling the water away from the Earth's surface, while the bulge at a is caused by the Moon pulling the Earth away from the water.