Roger Freedman • Robert Geller • William Kaufmann III

# *Universe*

Tenth Edition

## Chapter 4

## Gravitation and the Waltz of Planets

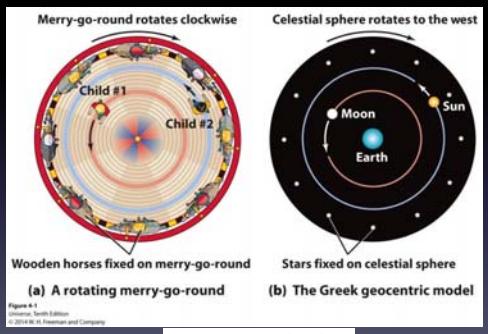
*By reading this chapter, you will learn*

- 4-1 How ancient astronomers attempted to explain the motions of the planets
- 4-2 What led Copernicus to a Sun-centered model of planetary motion
- 4-3 How Tycho's naked-eye observations of the sky revolutionized ideas about the heavens
- 4-4 How Kepler deduced the shapes of the orbits of the planets

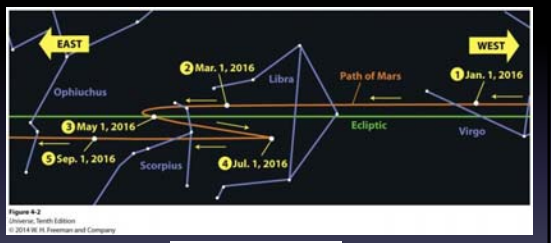
*By reading this chapter, you will learn*

- 4-5 How Galileo's pioneering observations with a telescope supported a Sun-centered model
- 4-6 The ideas behind Newton's laws, which govern the motion of all physical objects, including the planets
- 4-7 Why planets stay in their orbits and don't fall into the Sun
- 4-8 What causes ocean tides on Earth

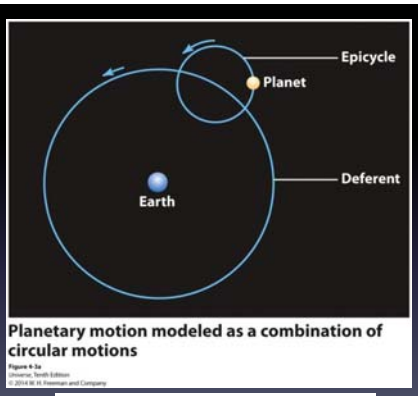
4-1: Ancient astronomers invented geocentric models to explain planetary motion



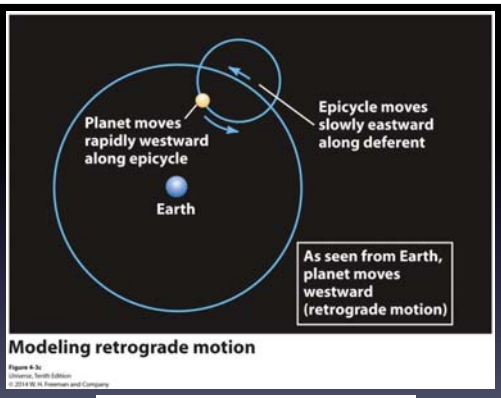

A Merry-Go-Round Analogy



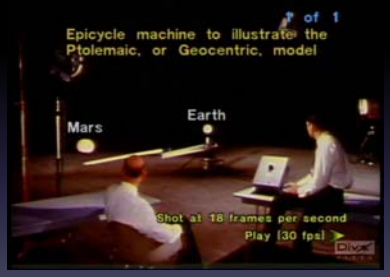

The Path of Mars in 2016




A Geocentric Explanation of Retrograde Motion

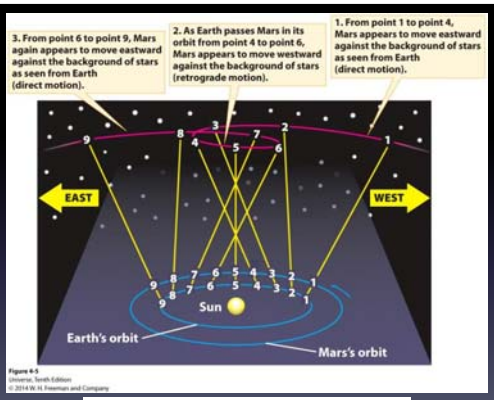



A Geocentric Explanation of Retrograde Motion



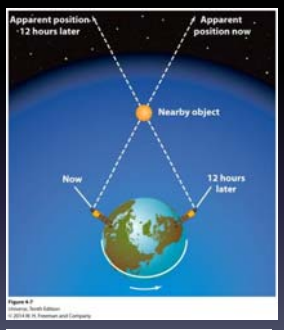

4-2: Nicolaus Copernicus devised the first comprehensive heliocentric model.

Nicolaus Copernicus (1473-1543)

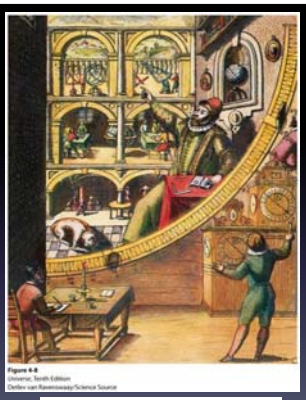



A Heliocentric Explanation of Retrograde Motion


4-3: Tycho Brahe's astronomical observations disproved ancient ideas about the heavens.




A Nearby Object Shows a Parallax Shift



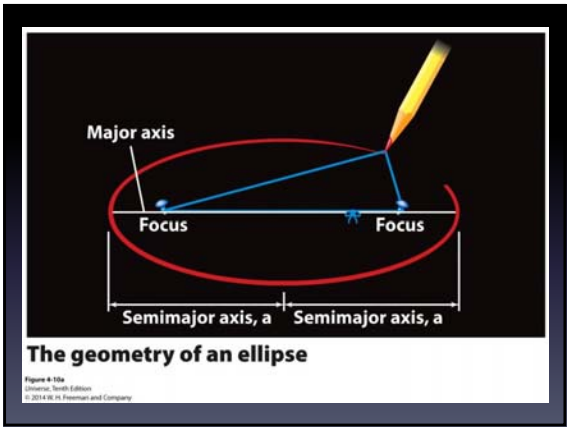
Tycho Brahe (1546-1601) Observing

4-4: Johannes Kepler proposed elliptical paths for the planets around the sun.

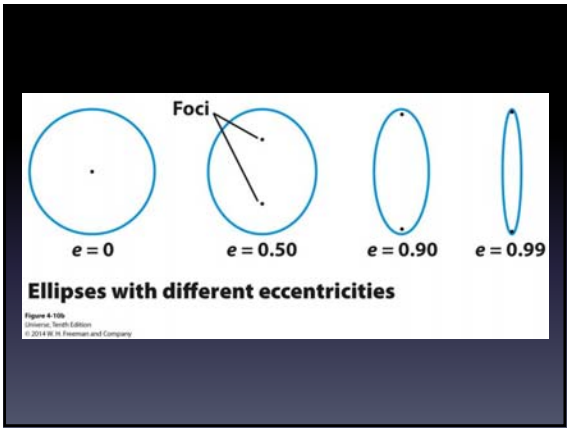
Johannes Kepler (1571-1630)

## Kepler's Three Laws of Planetary Motion

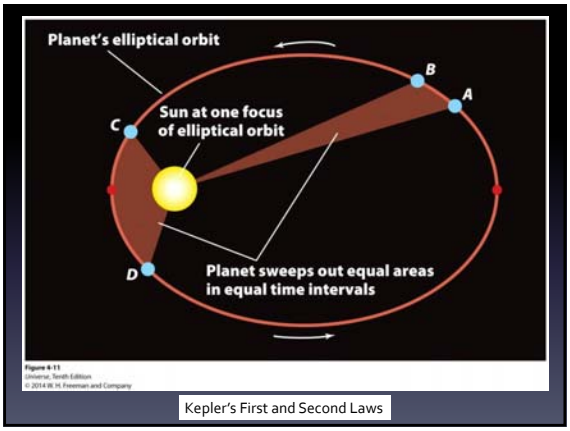
- A planet orbits the Sun in an ellipse with the Sun at one focus
- A planet sweeps out equal areas in equal times
- The square of a planet's period is proportional to the cube of its mean radius




The geometry of an ellipse




Ellipses with different eccentricities




Kepler's First and Second Laws

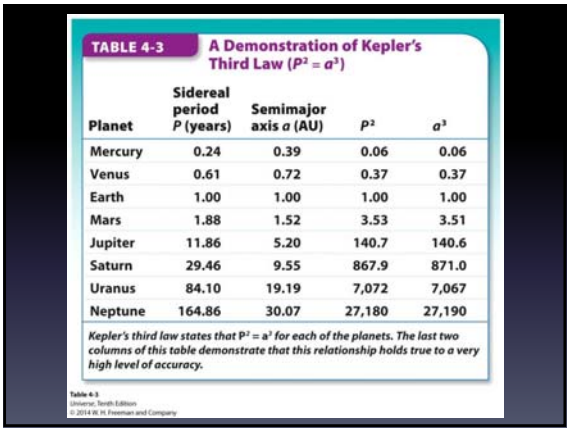


**TABLE 4-3** A Demonstration of Kepler's Third Law ($P^2 = a^3$)

| Planet | Sidereal period $P$ (years) | Semimajor axis $a$ (AU) | $P^2$ | $a^3$ |
|---|---|---|---|---|
| Mercury | 0.24 | 0.39 | 0.06 | 0.06 |
| Venus | 0.61 | 0.72 | 0.37 | 0.37 |
| Earth | 1.00 | 1.00 | 1.00 | 1.00 |
| Mars | 1.88 | 1.52 | 3.53 | 3.51 |
| Jupiter | 11.86 | 5.20 | 140.7 | 140.6 |
| Saturn | 29.46 | 9.55 | 867.9 | 871.0 |
| Uranus | 84.10 | 19.19 | 7,072 | 7,067 |
| Neptune | 164.86 | 30.07 | 27,180 | 27,190 |

*Kepler's third law states that $P^2 = a^3$ for each of the planets. The last two columns of this table demonstrate that this relationship holds true to a very high level of accuracy.*

Table 4-3
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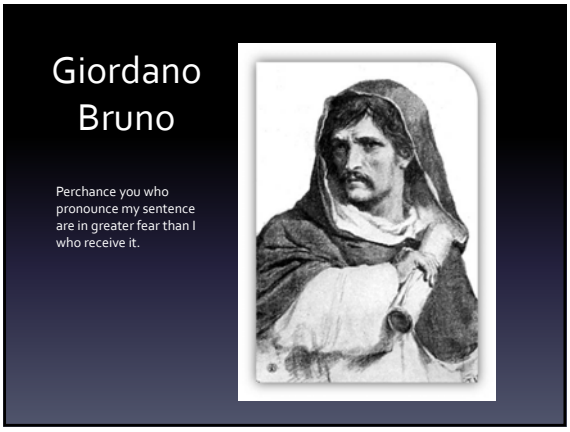
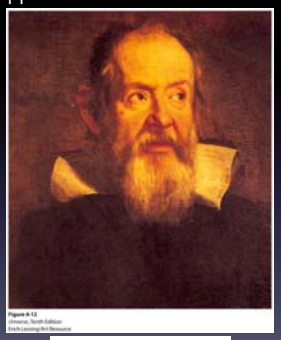


## Giordano Bruno

Perchance you who pronounce my sentence are in greater fear than I who receive it.

## 4-5: Galileo's discoveries with a telescope strongly supported a heliocentric model



Galileo Galilei (1564-1642)

## Early Studies

- He finds the period motion of a pendulum fascinating
- Times each swing of the chandelier with his pulse
- Periodic motion is fundamental in understanding gravity planetary motion
  - Tower of Pisa story apocryphal
- Experimentalist

## Gravity

- Calculates the acceleration of gravity by rolling spheres down a ramp
- Investigates the trajectory of projectiles
  - In 1537 Italian scientist Tartaglia said that the trajectory of a bullet was really a continuous curve
- Says objects fall with the same acceleration, regardless of weight, contradicting Aristotle
  - If two objects are attached, do they fall faster?

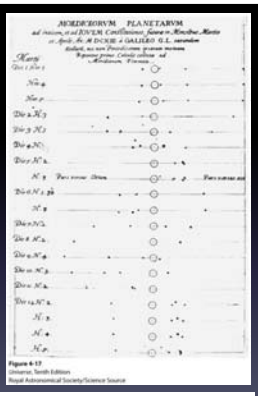
## NASA Proves it!

## 1609

- Galileo obtains a telescope from Flemish opticians
  - Invented by Hans Lippershey in 1608
  - Galileo improves upon it
- Always practical, Galileo tries to sell it to merchants
  - Affords a two hour advanced warning of incoming ships

## Always curious:

- Galileo points his telescope skyward
- Sees ten times further than any man before
- Traditional cosmology called into serious question
- Sees the Moon is not perfect but covered with mountains and valleys

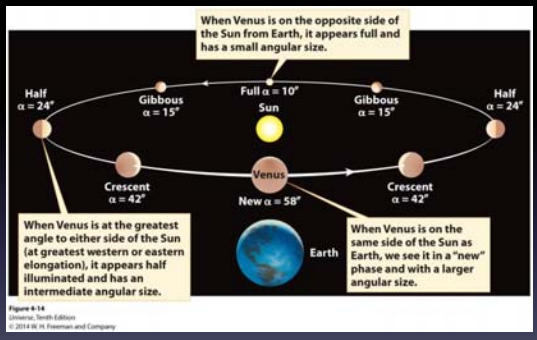


Early Observations of Jupiter's Moons

Jupiter and its Largest Moons

## Imperfection

- Galileo sees that the Sun is covered with spots
  - Not the perfect Sun professed by the Church
- Moving sunspots shows that the Sun rotates


The Changing Appearance of Venus Explained in a Heliocentric Model

## Facing the Inquisition

4-6: Newton formulated laws of motion and gravity that describe fundamental properties of physical reality.

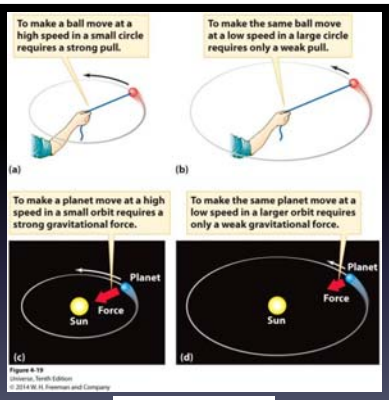
Isaac Newton (1642-1727)

$$F = G\frac{mM}{r^2}$$

- The solution to the ellipse question combines Kepler's third law, calculus, and Newton's laws of motion
- The Law of Universal Gravitation: every mass in the universe attracts every other mass with a force equal to the product of their masses and inversely proportional to the square of the distance between them

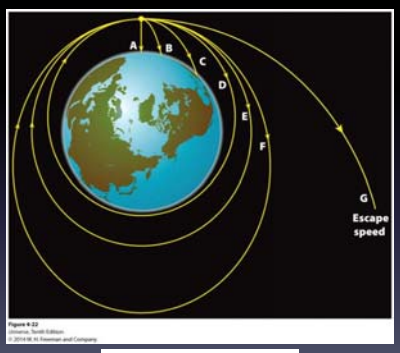
## Consequences

- Gravity makes orbits
  - The apple myth
- Newton offered no explanation as to why gravity worked this way
- Newton had to abandon a matter-filled universe for one of forces across empty space
- Newton had to invoke Providence to explain why the Universe hasn't collapsed



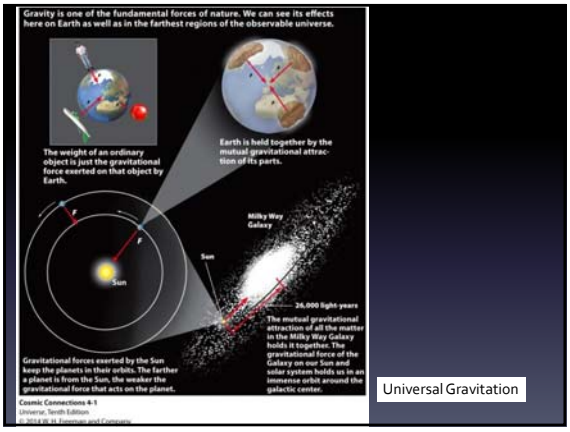

An Lame Orbit Analogy

4-7: Describing orbits with gravity



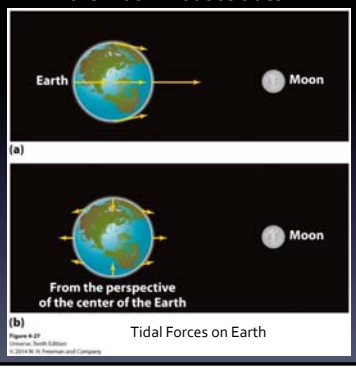

Orbits and the Escape Speed

## Freefall

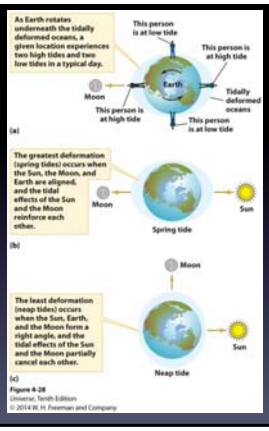



Universal Gravitation

## 4-8 Gravitational forces between Earth and the Moon Produce tides

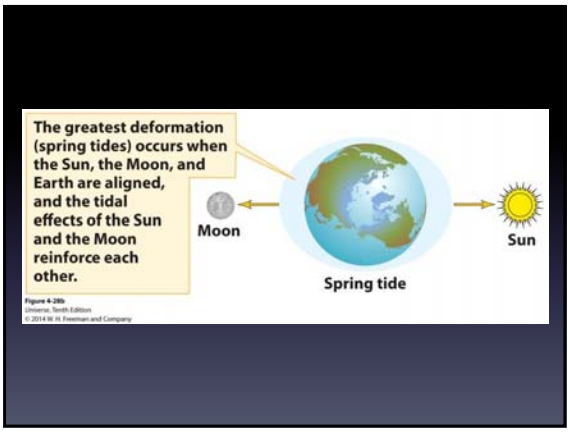


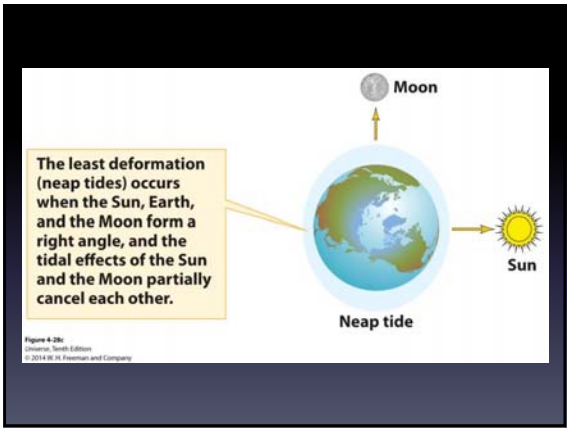

Tidal Forces on Earth

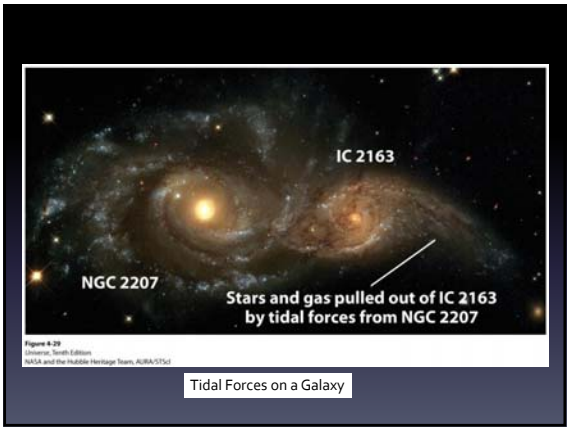



High and Low Tides

*Close-ups follow*




Tidal Forces on a Galaxy

## Key Ideas

- **Apparent Motions of the Planets:** Like the Sun and Moon, the planets move on the celestial sphere with respect to the background of stars. Most of the time a planet moves eastward in direct motion, in the same direction as the Sun and the Moon, but from time to time it moves westward in retrograde motion.
- **The Ancient Geocentric Model:** Ancient astronomers believed the Earth to be at the center of the universe. They invented a complex system of epicycles and deferents to explain the direct and retrograde motions of the planets on the celestial sphere.

## Key Ideas

- **Copernicus's Heliocentric Model:** Copernicus's heliocentric (Sun-centered) theory simplified the general explanation of planetary motions.
- In a heliocentric system, the Earth is one of the planets orbiting the Sun.
- A planet undergoes retrograde motion as seen from Earth when the Earth and the planet pass each other.
- The sidereal period of a planet, its true orbital period, is measured with respect to the stars. Its synodic period is measured with respect to the Earth and the Sun (for example, from one opposition to the next).

## Key Ideas

- **Kepler's Improved Heliocentric Model and Elliptical Orbits:** Copernicus thought that the orbits of the planets were combinations of circles.
- Using data collected by Tycho Brahe, Kepler deduced three laws of planetary motion.
  - (1) the orbits are in fact ellipses
  - (2) a planet's speed varies as it moves around its elliptical orbit
  - (3) the orbital period of a planet is related to the size of its orbit.

## Key Ideas

- **Evidence for the Heliocentric Model:** The invention of the telescope led Galileo to new discoveries that supported a heliocentric model. These included his observations of the phases of Venus and of the motions of four moons around Jupiter.

## Key Ideas

- Newton's laws of motion and Newton's law of universal gravitation can be used to deduce Kepler's laws. They lead to extremely accurate descriptions of planetary motions.
- The mass of an object is a measure of the amount of matter in the object. Its weight is a measure of the force with which the gravity of some other object pulls on it.

## Key Ideas

- In general, the path of one object about another, such as that of a planet or comet about the Sun, is one of the curves called conic sections: circle, ellipse, parabola, or hyperbola.
- **Tidal Forces:** Tidal forces are caused by differences in the gravitational pull that one object exerts on different parts of a second object.
- The tidal forces of the Moon and Sun produce tides in the Earth's oceans.
- The tidal forces of the Earth have locked the Moon into synchronous rotation.