The Origin of Modern Astronomy

Archeoastronomy
Ancient Astronomy
The Copernican Revolution
Copernicus
Brahe
Kepler
Galilei
Newton
Many early civilizations have left archeological sites demonstrating their interest in the heavens. They do not impact the development of Western astronomy.
Beginning of Western Astronomy

- Babylonians produced the first star catalogs c. 1600 BCE and they named constellations. The Venus tablet of Ammizaduga is so accurate that we can calculate its date exactly.
- Their purpose in pursuing astronomy was primarily to produce an accurate agricultural calendar.
- Secondarily it was for astrology.
- They made voluminous, accurate observations and they used measurements of cycles to predict astronomical events.
- Egyptian astronomy was used to align the pyramids and predict the flooding of the Nile river. The names of their constellations changed with different dynasties.
Cosmology of the Ancient Near East
Aristotle (384–322 BCE)
Elements of his physics affected peoples perception of the universe until modern times
- One perfect, unchangeable element—quintessence
  - Made the heavenly spheres
- Four changeable elements
  - Fire
  - Air
  - Water
  - Earth
- Motion always required a force
Aristarchus proposed a heliocentric universe. Motion of the Earth around the Sun should result in an observable parallax, which was not seen by the Greeks. It was not observed until 1838 by Bessel for 61 Cygni.

Aristotle and others rejected Aristarchus' proposal and adopted a geocentric model for the universe.
The problem for a geocentric universe was to explain the retrograde (westward) motion of the planets. Hipparchus invented deferents and epicycles to explain retrograde motion.
Claudius Ptolemy (c. 140 CE) “perfected” the geocentric model with the equant.

The Ptolemaic system was considered the “standard model” of the universe for ~1400 years.
Nicolaus Copernicus (1473-1543)

- Proposed a heliocentric model of the universe for philosophical reasons
- Wrote *De Revolutionibus*
- Copernican System
  - No one center for all celestial spheres
  - Planets revolve around the Sun in uniform circular motion
  - Earth’s distance to the fixed stars is much farther away than its distance to the Sun
  - Daily motion of the Sun results from Earth rotating on its axis
  - Annual motion of the Sun results from Earth revolving in its orbit around the Sun
  - Retrograde motion of the outer planets occurs when Earth overtakes outer planets
Tycho Brahe (1546–1601)

- Used high-precision instruments for precise astronomical observations, meticulously reported in tables.
- Rejected the Copernican system because he could not observe heliocentric parallax.
- Observations of comets demonstrated they would penetrate the celestial spheres so he created his own model.
A Quadrant Designed by Brahe

Used to precisely measure an object’s angular distance above the horizon.

He was restricted to unaided visual observations.

He knew the precision of his observations to be ~10’ of arc (a precision of 1” is needed to observe heliocentric parallax).
Johannes Kepler (1571–1630)

Used the precise observational tables of Tycho Brahe to study planetary motion mathematically.

Found a consistent description by abandoning both:

1. Circular motion and
2. Uniform motion.

- Planets move around the Sun on elliptical paths, with non-uniform velocities.
Kepler’s Laws of Planetary Motion

1. The Law of Ellipses: The orbits of the planets are ellipses with the Sun at one focus.

Eccentricity: $e = \frac{c}{a}$
Eccentricities of Ellipses

1) $e = 0.02$

2) $e = 0.1$

3) $e = 0.2$

4) $e = 0.4$

5) $e = 0.6$
2. The Law of Equal Areas: A line from a planet to the Sun sweeps over equal areas in equal intervals of time.
3. **The Harmonic Law**: A planet’s orbital period \((P)\) squared is proportional to its average distance from the Sun \((a)\) cubed:

\[
P_y^2 = a_{AU}^3
\]

\((P_y = \text{period in years}; a_{AU} = \text{distance in AU})\)

### TABLE 2.1 Some Solar System Dimensions

<table>
<thead>
<tr>
<th>Planet</th>
<th>Orbital Semimajor Axis, (a) (AU)</th>
<th>Orbital Period, (P) (years)</th>
<th>Orbital Eccentricity, (e)</th>
<th>(P^2/a^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.387</td>
<td>0.241</td>
<td>0.206</td>
<td>1.002</td>
</tr>
<tr>
<td>Venus</td>
<td>0.723</td>
<td>0.615</td>
<td>0.007</td>
<td>1.001</td>
</tr>
<tr>
<td>Earth</td>
<td>1.000</td>
<td>1.000</td>
<td>0.017</td>
<td>1.000</td>
</tr>
<tr>
<td>Mars</td>
<td>1.524</td>
<td>1.881</td>
<td>0.093</td>
<td>1.000</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.203</td>
<td>11.86</td>
<td>0.048</td>
<td>0.999</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.537</td>
<td>29.42</td>
<td>0.054</td>
<td>0.998</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.19</td>
<td>83.75</td>
<td>0.047</td>
<td>0.993</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.07</td>
<td>163.7</td>
<td>0.009</td>
<td>0.986</td>
</tr>
</tbody>
</table>
Comparison of Copernicus’ and Kepler’s Models

Accuracy of Mercury's position

Why isn’t the line for Kepler’s model straight?
Galileo Galilei (1564–1642)

Studied the physics of motion and discovered the Law of Inertia

He was the first to use the telescope to study astronomy
Galileo’s Telescope

He improved the newly invented telescope for astronomical use (But he did NOT invent the telescope!)

He was the first to meticulously report telescope observations of the sky to support the Copernican model of the universe.
Major Discoveries of Galileo

- Moons of Jupiter
  (4 Galilean moons)

- Rings of Saturn
  (This is a diagram of what he reported seeing. He called them "ears")
Major Discoveries of Galileo

Sun has **sunspots** and rotates
Moon has **mountains** and **valleys**
Major Discoveries of Galileo

Phases of Venus (including “full Venus”), proving that Venus orbits the Sun, not Earth!
Isaac Newton (1643 - 1727)

*Philosophiae Naturalis
Principia Mathematica*
(1687)

- Discovery of calculus
- Laws of motion
- Law of gravity
- Applied all of the above to solve the problem of planetary motion from first principles
Newton’s Laws of Motion

Newton’s First Law (Law of Inertia):

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. It is the basis for the Laws of Conservation of Momentum (linear and angular).
Newton’s Laws of Motion

Newton’s Second Law (Force Law):
When a force is exerted on an object, its acceleration is inversely proportional to its mass:

\[ a = \frac{F}{m} \]

Newton’s Third Law (Reaction Law):
When object A exerts a force on object B, object B exerts an equal and opposite force on object A.
Newton’s Law of Gravity

On the Earth’s surface, the acceleration of gravity is approximately constant (9.8 m/s/s, 32 ft/s²) and directed toward center of Earth. In equations the acceleration of gravity is represented by the symbol \( g \), e.g. \( F = mg \).

Note that the downward motion of the ball is governed by gravity and inertia (momentum). The forward motion is governed only by inertia (momentum).
Newton’s Law of Gravity

For two massive objects, gravitational force is proportional to the product of their masses \((m_1, m_2)\) divided by the square of the distance \((r)\) between them. It is an example of an inverse square law.
Newton’s Law of Gravity

The constant $G$ is called the universal gravitational constant. Its value was unknown to Newton and it was first measured by Henry Cavendish in 1798. In SI units it is:

$$G = 6.67 \times 10^{-11} \text{ N m}^2/\text{kg}^2$$
Using calculus, the laws of motion and the law of gravity, Newton was able to derive all three of Kepler’s laws.

1. The Law of Ellipses
2. The Law of Equal Areas
3. The Harmonic Law

$$(m_1 + m_2) G P^2 = 4\pi^2 a^3$$

Where $m_1$ and $m_2$ are the masses of each body, $G$ is the universal gravitational constant. For solar planets, the mass of the planet is insignificant to the mass of the Sun.
Understanding Orbital Motion

The universal law of gravity allows us to understand orbital motion of planets and satellites:

Example:

- Earth and Moon attract each other by gravitational force.
- Since Earth is much more massive than the Moon, the Moon’s effect on Earth is small.
- Earth’s gravitational force constantly accelerates the Moon towards Earth.
- This acceleration is constantly changing the Moon’s direction of motion, holding it on its almost circular orbit.
Orbital Motion

In order to stay on a closed orbit, an object has to be within a certain range of velocities:

Too slow: Object falls back down to Earth

Too fast: Object escapes the Earth’s gravity