Gravitation and the Waltz of the Planets

Chapter Four
Guiding Questions

1. How did ancient astronomers explain the motions of the planets?
2. Why did Copernicus think that the Earth and the other planets go around the Sun?
3. How did Tycho Brahe attempt to test the ideas of Copernicus?
4. What paths do the planets follow as they move around the Sun?
5. What did Galileo see in his telescope that confirmed that the planets orbit the Sun?
6. What fundamental laws of nature explain the motions of objects on Earth as well as the motions of the planets?
7. Why don’t the planets fall into the Sun?
8. What keeps the same face of the Moon always pointed toward the Earth?
Ancient astronomers invented geocentric models to explain planetary motions.

- 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.
• 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
A rotating merry-go-round

Merry-go-round rotates clockwise

Child #1

Child #2

Wooden horses fixed on merry-go-round
The Greek geocentric model

Celestial sphere rotates to the west

Stars fixed on celestial sphere
As seen from Earth, the planet moves eastward (direct motion).

- Planet moves rapidly eastward along epicycle.
- Epicycle moves slowly eastward along deferent.
As seen from Earth, planet moves westward (retrograde motion).

Planet moves rapidly westward along epicycle.

Epicycle moves slowly eastward along deferent.
Nicolaus Copernicus devised a comprehensive 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
- The sidereal period of a planet, its true orbital period, is measured with respect to the stars
A planet undergoes retrograde motion as seen from Earth when the Earth and the planet pass each other.
A planet’s synodic period is measured with respect to the Earth and the Sun (for example, from one opposition to the next)
<table>
<thead>
<tr>
<th>Planet</th>
<th>Copernican value (AU*)</th>
<th>Modern value (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.38</td>
<td>0.39</td>
</tr>
<tr>
<td>Venus</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>Earth</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Mars</td>
<td>1.52</td>
<td>1.52</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.22</td>
<td>5.20</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.07</td>
<td>9.55</td>
</tr>
<tr>
<td>Uranus</td>
<td>—</td>
<td>19.19</td>
</tr>
<tr>
<td>Neptune</td>
<td>—</td>
<td>30.07</td>
</tr>
<tr>
<td>Pluto</td>
<td>—</td>
<td>39.54</td>
</tr>
</tbody>
</table>

*1 AU = 1 astronomical unit = average distance from the Earth to the Sun.
<table>
<thead>
<tr>
<th>Planet</th>
<th>Synodic period</th>
<th>Sidereal period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>116 days</td>
<td>88 days</td>
</tr>
<tr>
<td>Venus</td>
<td>584 days</td>
<td>225 days</td>
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<tr>
<td>Earth</td>
<td>—</td>
<td>1.0 year</td>
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<tr>
<td>Mars</td>
<td>780 days</td>
<td>1.9 years</td>
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<tr>
<td>Jupiter</td>
<td>399 days</td>
<td>11.9 years</td>
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<tr>
<td>Saturn</td>
<td>378 days</td>
<td>29.5 years</td>
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<tr>
<td>Uranus</td>
<td>370 days</td>
<td>84.1 years</td>
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<tr>
<td>Neptune</td>
<td>368 days</td>
<td>164.9 years</td>
</tr>
<tr>
<td>Pluto</td>
<td>367 days</td>
<td>248.6 years</td>
</tr>
</tbody>
</table>
Tycho Brahe’s astronomical observations provided evidence for another model of the solar system.
Parallax – apparent difference in position of object viewed from two different locations
Johannes Kepler proposed elliptical paths for the planets about the Sun

- Using data collected by Tycho Brahe, Kepler deduced three laws of planetary motion:
  - the orbits are ellipses
    - With Sun at one focus
  - Equal areas in equal times
    - a planet’s speed varies as it moves around its elliptical orbit
  - The period squared equals the semi-major axis cubed
    - the orbital period of a planet is related to the size of its orbit
Kepler’s First Law

- Major axis
- Focus
- Semimajor axis
- Focus
- Semimajor axis
Kepler’s Second Law

- Sun at one focus of elliptical orbit
- Planet sweeps out equal areas in equal time intervals
## Kepler’s Third Law

### A Demonstration of Kepler’s Third Law \((P^2 = a^3)\)

<table>
<thead>
<tr>
<th>Planet</th>
<th>Sidereal period (P) (years)</th>
<th>Semimajor axis (a) (AU)</th>
<th>(P^2)</th>
<th>(a^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.24</td>
<td>0.39</td>
<td>0.06</td>
<td>0.06</td>
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<tr>
<td>Venus</td>
<td>0.61</td>
<td>0.72</td>
<td>0.37</td>
<td>0.37</td>
</tr>
<tr>
<td>Earth</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Mars</td>
<td>1.88</td>
<td>1.52</td>
<td>3.53</td>
<td>3.51</td>
</tr>
<tr>
<td>Jupiter</td>
<td>11.86</td>
<td>5.20</td>
<td>140.7</td>
<td>140.6</td>
</tr>
<tr>
<td>Saturn</td>
<td>29.46</td>
<td>9.55</td>
<td>867.9</td>
<td>871.0</td>
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<tr>
<td>Uranus</td>
<td>84.10</td>
<td>19.19</td>
<td>7,072</td>
<td>7,067</td>
</tr>
<tr>
<td>Neptune</td>
<td>164.86</td>
<td>30.07</td>
<td>27,180</td>
<td>27,190</td>
</tr>
<tr>
<td>Pluto</td>
<td>248.60</td>
<td>39.54</td>
<td>61,800</td>
<td>61,820</td>
</tr>
</tbody>
</table>

\[P^2 = a^3\]

\(P = \) planet’s sidereal period, in years

\(a = \) planet’s semimajor axis, in AU
Galileo’s discoveries with a telescope strongly supported a heliocentric model

- Galileo’s observations reported in 1610
  - the phases of Venus*
  - the motions of the moons of Jupiter*
  - “mountains” on the Moon
  - Sunspots on the Sun

*observations supporting heliocentric model
• One of Galileo’s most important discoveries with the telescope was that Venus exhibits phases like those of the Moon
• Galileo also noticed that the apparent size of Venus as seen through his telescope was related to the planet’s phase
• Venus appears small at gibbous phase and largest at crescent phase
There is a correlation between the phases of Venus and the planet’s angular distance from the Sun.
Geocentric Model Issues

- To explain why Venus is never seen very far from the Sun, the Ptolemaic model had to assume that the deferents of Venus and of the Sun move together in lockstep, with the epicycle of Venus centered on a straight line between the Earth and the Sun.

- In this model, Venus was never on the opposite side of the Sun from the Earth, and so it could never have shown the gibbous phases that Galileo observed.
• In 1610 Galileo discovered four moons of Jupiter, also called the Galilean moons or satellites.

• This is a page from his published work in 1610.
Telescope Photograph of Jupiter & the Galilean Moons
Isaac Newton formulated three laws that describe fundamental properties of physical reality

- Called Newton’s Laws of Motion, they apply to the motions of objects on Earth as well as in space
  - a body remains at rest, or moves in a straight line at a constant speed, unless acted upon by an outside force
    - the law of inertia
  - the force on an object is directly proportional to its mass and acceleration
    - \( F = m \times a \)
  - the principle of action and reaction
    - whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first body
Newton’s Law of Universal Gravitation

\[ F = G \left( \frac{m_1 m_2}{r^2} \right) \]

\( F \) = gravitational force between two objects
\( m_1 \) = mass of first object
\( m_2 \) = mass of second object
\( r \) = distance between objects
\( G \) = universal constant of gravitation

- If the masses are measured in kilograms and the distance between them in meters, then the force is measured in Newtons
- Laboratory experiments have yielded a value for \( G \) of

\[ G = 6.67 \times 10^{-11} \text{ Newton} \cdot \text{m}^2/\text{kg}^2 \]
Newton’s description of gravity accounts for Kepler’s laws and explains the motions of the planets and other orbiting bodies.
Orbital Motion

- The law of universal gravitation accounts for planets not falling into the Sun nor the Moon crashing into the Earth.
- Paths A, B, and C do not have enough horizontal velocity to escape Earth’s surface whereas Paths D, E, and F do.
- Path E is where the horizontal velocity is exactly what is needed so its orbit matches the circular curve of the Earth.
Orbits follow any one of the family of curves called conic sections.
A Comet: An Example of Orbital Motion
Gravitational forces between two objects produce tides in distant regions of the universe.
Understanding Tidal Forces

(a) Billiard balls at rest

(b) Path of the balls:
- A short distance
- A longer distance
- A still longer distance, a short time later

(c) From the perspective of the center ball
The yellow arrows indicate the strength and direction of the Moon’s gravitational pull at selected points on the Earth.
From the perspective of the center of the Earth

The yellow arrows indicate the strength and direction of the Moon’s tidal forces acting on the Earth.
This person is at low tide

This person is at high tide

This person is at high tide

This person is at low tide

Moon

Oceans

Earth
(a) GRAVITATIONAL FORCE
Bulge of water

“Balance point” or center of mass of the earth-moon system

(b) CENTRIFUGAL FORCE
Two resultant bulges of water

(c) GRAVITATIONAL AND CENTRIFUGAL FORCE
Key Words

- acceleration
- aphelion
- conic section
- conjunction
- deferent
- direct motion
- eccentricity
- ellipse
- elongation
- epicycle
- focus
- force
- geocentric model
- gravitational force
- gravity
- greatest eastern and western elongation
- heliocentric model
- hyperbola
- inferior conjunction
- inferior planet
- Kepler’s laws
- law of equal areas
- law of inertia
- law of universal gravitation
- major axis
- mass
- Neap and spring tides
- Newtonian mechanics
- Newton’s laws of motion
- Newton’s form of Kepler’s third law
- Occam’s razor
- opposition
- parabola
- parallax
- perihelion
- period (of a planet)
- Ptolemaic system
- retrograde motion
- semimajor axis
- sidereal period
- speed
- superior conjunction
- superior planet
- synodic period
- tidal forces
- universal constant of gravitation
- velocity
- weight