Renaissance Astronomy
ASTR 2110
Sarazin

Astronomical Clock in Prague
A Timeline for Astronomical Discovery

- Copernicus
- Galileo
- Kepler
- Halley
- Darwin

Timeline:
- 1500: Columbus
- 1572: Tycho's Supernova
- 1609: First use of telescope
- 1618: Kepler's laws published
- 1687: Principia published
- 1665: Abberation of starlight
- 1759: Halley's Comet returns
- 1801: Uranus discovered
- 1837: Origin of Species
- 1846: Neptune discovered
- 1874: Wallace
Sidereal and Synodic Periods

Period = time for planet to orbit the Sun

Sidereal period = real period

Synodic period = apparent period as seen from Earth

![Diagram of Earth's and Venus' orbits with first and second inferior conjunctions](image)
Periods: Ptolemy’s Theory

0.32  1.60  1.0  2.14  1.09  1.03  1.0
Periods: Copernicus Theory

Earth-Moon
Venus
Mercury
Mars
Jupiter
Saturn

0.24 0.62 1.00 1.88 11.86 29.41
Computing relative sizes of orbits in the Copernican system
Astronomical Unit (AU)

- Right-sized distance unit for Solar System, exoplanetary systems, binary stars
- Average distance from Earth to Sun
  
  \[ 1 \text{ AU} = 1.50 \times 10^{13} \text{ cm} = 1.50 \times 10^{11} \text{ m} \]

- \(~92\text{ million miles, 150 million km}\)
Advantages of the Copernican System

- Simpler in concept
- Natural explanation for the annual motion of the Sun against the background stars
- Natural explanation of retrograde motion
- Relative spacing of planetary orbits determined, periods made sense
- Natural explanation for motion of Venus and Mercury relative to the Sun

But: not more accurate than Ptolemaic tables (because circular orbits assumed)
The Copernican Revolution

• “Cosmic Connection”
  – We live on a planet like many others moving about a star like many others in a galaxy like many others. We are part of the Universe. We are not special.

• Simplicity of nature
  – Natural laws are simple, but can result in complex phenomena

• Predictive power of theories
The Empire Strikes Back

Catholic church moves to suppress new thinking, due in part to the Reformation

Giordano Bruno: builds on Copernicus. Suggests other planets may also have intelligent life
A Timeline for Astronomical Discovery
Galileo Galilei (1564-1642)
Galileo

• First great experimenter
  – Theories must correctly predict the results of experiments
  – Predictions must be quantitative

• Studied motion and gravity
  – Inertia (heavier objects harder to stop)
  – Gravity (all things fall at the same rate)
  – Time (pendulum)
  – Relativity

• First astronomy telescope
Telescopic Observations

Galileo did not invent telescope, but was first to use it for astronomy.

Observations called into question the Ptolemaic cosmology.

First described in book *Sidereus Nuncius*.
The Moon

Aristotelian Concept: Celestial bodies are perfect

Observation: mountains, craters, valleys on the Moon
The Sun

Aristotelian Concept:
Celestial bodies are perfect

Observation:
Sunspots, rotation of the Sun
The Milky Way

Aristotelian Concept: Stars are located on a fixed celestial sphere.

Observation: Many more stars than visible to the naked eye. Suggest stars are very distant.
The moons of Jupiter

The View through a telescope

Everything does NOT orbit the Earth

A page from Galileo’s notes
Key Observational Test: Phases of Venus

Proves that Venus shines by reflected sunlight

Provides an absolute, yes or no test of Ptolemy vs. Copernicus
Phases of Venus - Copernicus
Phases of Venus - Ptolemy
Final Jeopardy, for all the money

Perfect observational test

1) If Venus *ever* has gibbous phases (more than half full), then Ptolemy is wrong

2) If Venus *never* has gibbous phases, then Copernicus is wrong
Phases of Venus
Phases of Venus - Copernicus
Galileo: Troubles with Catholic Church

- First book *Sidereus Nuncius* controversial
- Galileo ordered to stop defending Copernican theory
- In 1632, published *Dialogo dei Due Massimi Sistemi* (Dialogue Concerning the Two Chief World Systems)
- Put on trial by Inquisition, ordered to recant, put under house arrest
Galileo’s Finger
Renaissance Astronomy 2
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Brahe’s Observatory on Hveen
Tycho Brahe (1545-1601)

Last and greatest of the pre-telescopic observers
A Timeline for Astronomical Discovery

- Galileo
- Copernicus
- Kepler
- Brahe
- Newton
- Halley
- Herschel
- Wallace
- Columbus
- Tycho's Supernova
- Abberation of starlight
- Origin of Species
- Neptune discovered
- Uranus discovered
- Halley's Comet returns
- Principia published
- First use of telescope
- de Revolutionibus published
- 1500 - 1600 - 1700 - 1800 - 1900
Tycho Brahe
Tycho Brahe

- Greatest of pre-telescope observers in Europe
  - Tycho: tables based on both Ptolemaic and Copernican system inaccurate for planets
  - >20 years, measured positions of Sun, Moon and planets with unprecedented accuracy
Tycho’s Supernova

Tycho’s Supernova Of 1572
Comet (Halley’s comet)

- Comets: lack of parallax means beyond Moon, in Solar System
Tycho’s Observatory at Hveen
Tycho’s Observatory at Hveen
Tycho’s Model
Tycho’s End

- Exiled from Denmark
- Went to Prague, Imperial Mathematician
- >20 years of wonderful data, but needed someone to analyze it and compare to model (Kepler)
- Died in an interesting manner
Tycho’s End

One good thing is that at least Tycho Brahe did not die in Hveen!
Johannes Kepler (1571-1630)
A Timeline for Astronomical Discovery
Consumed by idea that laws of nature are simple & harmonious
Kepler’s first cosmological model

Kepler’s Perfect Solids
Music of the Spheres

Fig. 62.—The “music of the spheres,” according to Kepler. From the *Harmony of the World.*
Kepler

• Music of Spheres
• Mysterium Cosmographicum (1596), incorrect theory
• Tycho Brahe forced to leave Hveen and move to Prague in 1596.
• In 1600, he hired Johannes Kepler to help him model the motions of the planets, particularly Mars.
• When Brahe died unexpectedly, Kepler stole his notebooks containing detailed records of the position of Mars.
• Kepler used the data to discover the true nature of planetary orbits and published the results in Astronomia Nova in 1609.
Kepler’s 3 Laws of Planetary Motion

Shapes of orbits?
• 1st Law: Planet orbits are ellipses, with Sun at one focus

How do planets move?
• 2nd Law: Line from planet to Sun sweeps out equal areas in equal times

How are motions of different planets related?
• 3rd Law: Squares of the periods are proportion to cubes of the average distances from the Sun (semi-major axes of orbits)
Kepler’s 3 Laws of Planetary Motion

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Kepler’s First Law
Ellipses

\[ l_1 + l_2 = \text{constant} \]
Ellipses
Ellipses

- $a \equiv$ semimajor axis
- $b \equiv$ semiminor axis
- $e \equiv \frac{c}{a} = \text{eccentricity}$
- $b = a\sqrt{1 - e^2}$
Eccentricity
Eccentricity

e=0 (circle)
e=0.23

e=0.43

e=0.77

e=1 (line)
Ellipses

\[ l_1 + l_2 = \text{constant} \]
Ellipses

\[ l_1 + l_2 = 2a = \text{constant} \]
Ellipses

\[ l_1 + l_2 = 2a = \text{constant} \]
\[ l_1 = l_2 \text{ by symmetry} \]
\[ l_1 = l_2 = a \]
Average distance from focus

\[ d = l_1, \quad d' = l_2 \]
\[ l_1 + l_2 = 2a = \text{constant} \]
\[ \langle d, d' \rangle = \frac{d + d'}{2} = \frac{l_1 + l_2}{2} = \frac{2a}{2} = a \]
\[ \langle d \rangle = a \]
Perihelion, Aphelion

$\mathbf{r}_p$  $\mathbf{r}_a$
cosine law

\[ s_3^2 = s_1^2 + s_2^2 - 2s_1s_2 \cos(\phi) \]

\[ s_1 = r, \ s_2 = 2c, \ s_3 = r', \ \phi = \pi - \theta \]

\[ r'^2 = r^2 + (2c)^2 - 2r(2c)\cos(\pi - \theta) \]

\[ r' + r = 2a, \ r' = 2a - r, \ c = ae, \ \cos(\pi - \theta) = -\cos(\theta) \]
Ellipse – Polar Coordinates

\[ r'^2 = r^2 + (2c)^2 - 2r(2c)\cos(\pi - \theta) \]

\[ r' + r = 2a \Rightarrow r' = 2a - r, \quad c = ae, \quad \cos(\pi - \theta) = -\cos(\theta) \]

\[ 4d^2 - 4dr + r^2 = r'^2 + 4a^2e^2 + 4ae \cos(\theta) \]

\[ r[1 + e \cos(\theta)] = a - ae^2 \]
The equation for the distance $r$ from the focus to a point on the ellipse, expressed in terms of the semi-major axis $a$, eccentricity $e$, and angle $\theta$, is given by:

$$ r \left[ 1 + e \cos(\theta) \right] = a - ae^2 $$

Alternatively, the distance $r$ can be expressed as:

$$ r = \frac{a(1 - e^2)}{1 + e \cos(\theta)} $$
Ellipses = Conic Section
Conic sections
Conic Sections in Polar Coordinates

\[ r = \frac{r_p(1 + e)}{1 + e \cos(\theta)} \]

\( r_p \) = closest distance to focus (perhelion)
\( e = 0 \) circle
\( 0 \leq e < 1 \) ellipse
\( e = 1 \) parabola
\( e > 1 \) hyperbola
Kepler’s 3 Laws of Planetary Motion

Shapes of orbits?
• 1st Law: Planet orbits are ellipses, with Sun at one focus

How do planets move?
• 2nd Law: Line from planet to Sun sweeps out equal areas in equal times

How are motions of different planets related?
• 3rd Law: Squares of the periods are proportion to cubes of the average distances from the Sun (semi-major axes of orbits)
Kepler’s Second Law
Kepler’s 3 Laws of Planetary Motion

Shapes of orbits?
• 1st Law: Planet orbits are ellipses, with Sun at one focus

How do planets move?
• 2nd Law: Line from planet to Sun sweeps out equal areas in equal times

How are motions of different planets related?
• 3rd Law: Squares of the periods are proportion to cubes of the average distances from the Sun (semi-major axes of orbits)
Kepler’s Third Law

\[ P = \text{Period} = \text{time to orbit} \]
\[ a = \text{average distance} = \text{semimajor axis of orbit} \]
\[ P^2 \propto a^3 \]
\[ (\text{period})^2 \propto (\text{distance})^3 \]

Measure \( P \) in years, and \( a \) in AU

Earth is planet \( \rightarrow \) applies to Earth,
\[ P = 1 \text{ year, } a = 1 \text{ AU} \]
\[ P^2 = a^3 \]
\[ (\text{period})^2 = (\text{distance})^3 \]
Kepler’s Third Law

\[
\left( \frac{P}{\text{yr}} \right)^2 = \left( \frac{a}{\text{AU}} \right)^3
\]

\[
P_{\text{yr}}^2 = a_{\text{AU}}^3
\]
Kepler’s Third Law: Examples

- Semimajor axis of Earth’s orbit is 1 AU and period is 1 year. Thus:
  \[ 1^2 = 1^3 = 1 \]

- Semimajor axis of Mars’ orbit is 1.52 AU, and period is 1.88 years
  \[ 1.88^2 = 1.52^3 = 3.53 \]
## Properties of the Planets

<table>
<thead>
<tr>
<th>Name</th>
<th>Distance (AU)</th>
<th>Period (years)</th>
<th>Diameter (Earth=1)</th>
<th>Mass (Earth=1)</th>
<th>Density</th>
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<tbody>
<tr>
<td>Mercury</td>
<td>0.39</td>
<td>88 days</td>
<td>0.38</td>
<td>0.055</td>
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</tr>
<tr>
<td>Venus</td>
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<td>224 days</td>
<td>0.95</td>
<td>0.82</td>
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<td>Earth</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5.5</td>
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<tr>
<td>Mars</td>
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<td>1.88</td>
<td>0.53</td>
<td>0.11</td>
<td>3.9</td>
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<tr>
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<td>317.8</td>
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<td>84.07</td>
<td>4.0</td>
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<td>1.2</td>
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<tr>
<td>Neptune</td>
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<td>164.8</td>
<td>3.88</td>
<td>17.2</td>
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