Understanding Planetary Motion

- Use experimental observations (made prior to telescopes) to understand motion of the planets

- Leads to Kepler’s 3 laws of planetary motion

- Provides experimental observations which are later explained by physics developed by Galileo, Newton and others
Brahe and Kepler ➔

statue in Prague

• Brahe led team which collected data on position of planets (1580-1600 no telescopes). “commuted” between observatory in Denmark and Prague. Died in 1601.

• Kepler (mathematician) hired by/succeeded Brahe to analyze data. Determined 3 Laws of planetary motion (1600-1620). Mostly funded by Holy Roman Emperor to provide horoscopes (astrology)

• Input - 20 years of data on:

  angular position of planets
  approximate distances from Earth (accurate relative distances)

• Few “modern” tools (no calculus, no graph paper, no log tables) but we now know that repeated data taking improves accuracy by sqrt(N)
Apparent Shift = Parallax

- A moving observer sees fixed objects move.
- Near objects appear to move more than far objects.
- The effect is due to the change in observation point, and is used by our eyes for depth perception.

Geocentric parallax - Earth as base

Heliocentric parallax - use orbit about Sun as base. Use for stars as need telescope.

[Diagram showing Earth, Mars, and Jupiter with angles A and B]
Sources of Parallax

- Human eyes. Extend thumb out and have right eye open/left close and vice-versa. See how thumb “moves” compared to distant object.
- Common survey technique.
- Heliocentric parallax uses the sun as a base.
- Take a photo with telescope at two different seasons → come back to later for stars
- Geocentric parallax uses the earth as a base.
- Make a measurement two or more times in one night.
- Use for planets → Brahe’s data had (after analysis) distances to planets plus their position in sky
Observations of Brahe 1580-1600

• Brahe was a Danish nobleman who became famous after observing a supernova in 1572 and showing it was “far away” (no parallax)

• Danish king provided funding and an island where Brahe set up an observatory – no telescopes just sextants - that is long sticks to measure planet and star angles (positions in sky) which could be flipped to measure both E-W and N-S angle at same time. Accurate to 1 minute of arc (1/60 of a degree).

• In 1577 observes comet with non-zero small parallax, showing further away than Moon and moving through planet orbits. Idea of “celestial crystal spheres” – each planet on its own sphere which “carried” them around the sky – would not accommodate comet as moving “through” spheres and now know crystal sphere are nonsensical
Brahe’s Observatory
Kepler’s Data Analysis

• Kepler using Brahe data figured out correct orbital shape (circle vs ellipse vs circle within circle, etc)
• Mercury and Venus relatively easy. Orbit of Mercury part of assignment 3. Looks like an ellipse
• Mars, Jupiter and Saturn tougher, especially as Jupiter has 12 year orbit and Saturn 30 years → Kepler mostly did Mars as about 2 year orbit and so Brahe’s data had 10 orbits of Mars around the Sun
• Orbital period for all planets “easy”
• Distance better measured for closer. Ratio easier
Kepler’s Laws of Motion

• Mostly he used relative location of Mars after repeated orbits around the Sun. Mars is close and so most accurate measurements, and has a slightly less than 2 year period around the Sun.

• Kepler spent 4 years, with 70 hypotheses for Mar's orbit and over 900 pages of notes trying to determine the orbit of Mars

• A big step was realizing that Earth’s orbit about the Sun also wasn’t a circle, both Mars and Earth orbits are ellipses.

A Kepler drawing which has Earth either being a circle or an ellipse in its orbit about the Sun
Kepler’s Laws of Planetary Motion

#1: The orbit of a planet is an ellipse with the Sun at one focus (1604)
#2: The line joining a planet and the sun sweeps equal areas in equal time. (1607)
#3: The square of a planet’s period is proportional to the cube of the length of the orbit’s semimajor axis. (semimajor axis is about the same as the distance to the Sun) (1619)
Kepler’s Laws of Planetary Motion

FIRST LAW: The orbit of a planet is an ellipse with the sun at one focus.

A line connecting the two foci in the ellipse always has the same length. In an ellipse, the planet is sometimes closer to the Sun and sometimes further away.
Kepler’s Second Law

- The line joining a planet and the sun sweeps equal areas in equal time.

The planet moves slowly here when it is further away.

The planet moves quickly here when it is closer to the Sun.
Kepler’s Third Law

• The square of a planet’s period is proportional to the cube of the length of the orbit’s semimajor axis. Same as how long it takes to make one orbit depends on how far away the planet is from the Sun.

• Mathematically, $T^2/a^3 = \text{constant}$ (\(=1\) if use 1 Earth year and 1 AU as units).

• The constant is the same for all objects orbiting the Sun → same process determines all planets’ motions.
Third Law Example

- Jupiter compared to Earth
- If we measure that it takes Jupiter 11.9 years to orbit the Sun then:

\[
\text{distance}^3 (\text{Jupiter-Sun}) = \text{period}(\text{Jupiter})^2
\]

\[
\text{distance} = \text{period}^{2/3}
\]

\[
\text{distance} = (11.9 \times 11.9)^{1/3}
\]

\[
\text{distance} = (142)^{1/3} = 5.2 \text{ AU}
\]
<table>
<thead>
<tr>
<th></th>
<th>Mean Distance from Sun</th>
<th>Sidereal Orbital Period</th>
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<tbody>
<tr>
<td></td>
<td>AU</td>
<td>$P_e$</td>
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<tr>
<td>Mercury</td>
<td>0.387</td>
<td>0.241</td>
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<tr>
<td>Venus</td>
<td>0.723</td>
<td>0.615</td>
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<tr>
<td>Earth</td>
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<tr>
<td>Mars</td>
<td>1.524</td>
<td>1.881</td>
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<tr>
<td>Jupiter</td>
<td>5.203</td>
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<tr>
<td>Saturn</td>
<td>9.537</td>
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<td>Uranus</td>
<td>19.191</td>
<td>83.749</td>
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<tr>
<td>Neptune</td>
<td>30.069</td>
<td>163.727</td>
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</table>
Kepler → Galileo and Newton

- Kepler correctly determined the motion of the planets giving his 3 Laws which still hold today for the planets and other orbital motion: moons around planets, exoplanets around other stars, stars in the Milky Way about its center.
- Kepler did not address WHY. Simply what curve best matched orbits and some arithmetical relationships.
- The WHY was determined by physicists like Galileo and Newton.
- They needed to develop Physics as a science: understand motion, forces, and gravity.
Galileo 1564-1642

• Born in Pisa, Professor of art, mathematics, natural philosophy, astronomy in Pisa and Padua with occasional “contract” work for various Dukes especially in Florence

• Very strong proponent of the scientific method – use of observations to test theories. Possibly the greatest physicist/astronomer in history. Firm believer in Copernican model, seen in letters to Kepler.

• Early work: motion, and practical elements like hydrostatics

• 1609: first person to use a telescope for astronomy

Mostly while in Padua → became the most famous scientist/celebrity in Europe. He then moved to Florence. Became the most prominent proponent of new cosmology.

• Last 25 years of life was often in trouble with the Catholic Church over saying Sun at center of solar system. His powerful friends helped to save his life. More next class.
Kepler and Galileo

• They were contemporaries and wrote letters to each other. Both strong proponents of Sun-centered solar system. From 1596 Galileo letter to Kepler “I esteem myself happy to have as great an ally as you in my search for the truth...I have for many years been a partisan of the Copernican view....I have collected many proofs, but I do not publish them, because I am deterred by the fate of our teacher Copernicus...[who] was ridiculed and condemned by countless people (for very great is the number of the stupid)...

• Kepler’s Laws proved that the planets orbited the Sun but had a lot of “math”, 1620 book Epitome of Copernican Astronomy, and like Copernicus’ work hard for most people to understand.

• Starting in 1609, Galileo’s observations of Jupiter, Venus, Sun (next lecture) also proved planets orbited the Sun but were easier for most people to understand, and also “wow” items for early 17th century Europe → Galileo becomes famous but also the focus of Church.
Lecture Feedback

E-mail me a few sentences describing one topic you learned from this set of presentations. Please include the phrase “Parallax is the geometric technique that can be used to measure distance” in your mini-report but do not use that as your “one topic”.