Planetary Motion (con't)

- Experimental observations (made prior to telescopes) were used to understand motion of the planets
- Difference between "apparent motion" and "real" motion understood – key part of modern science.
- Lead to Kepler's 3 laws of planetary motion
- Provided experimental observations which are later explained by physics developed by Galileo, Newton and others

Brahe and Kepler

- Brahe led team which collected data on position of planets (1580-1600 no telescopes)
- Kepler (mathematician) hired by Brahe to analyze data. Determined 3 Laws of planetary motion (1600-1630)
- Input - 20 years of data on:

  angular position of planets

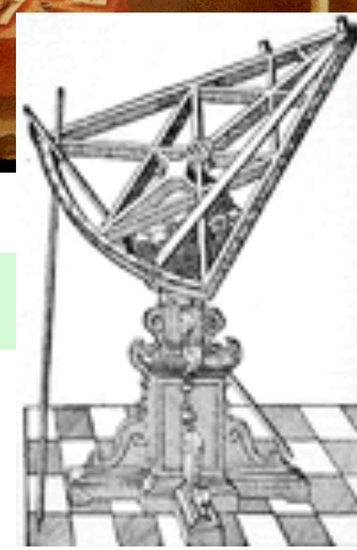
  approximate distances from Earth (accurate relative distances)
- Few "modern" tools (no calculus, no graph paper, no log tables)

Observations of Brahe 1580-1600

- Brahe was a Danish nobleman who became famous after observing a supernova and showing it was "far away"
- Danish king provided funding and an island where Brahe set up an observatory – no telescopes just (essentially) sextants - that is long sticks to measure angles which could be flipped to measure both E-W and N-S angle at same time

Brahe's Observatory

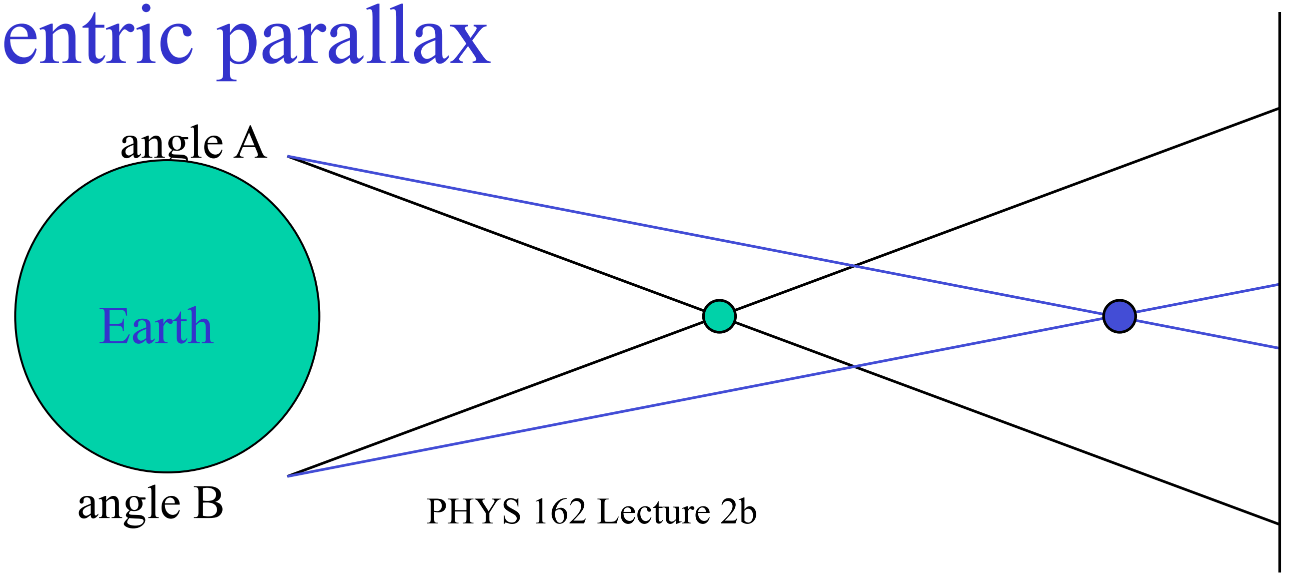
sextant



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



Sources of Parallax

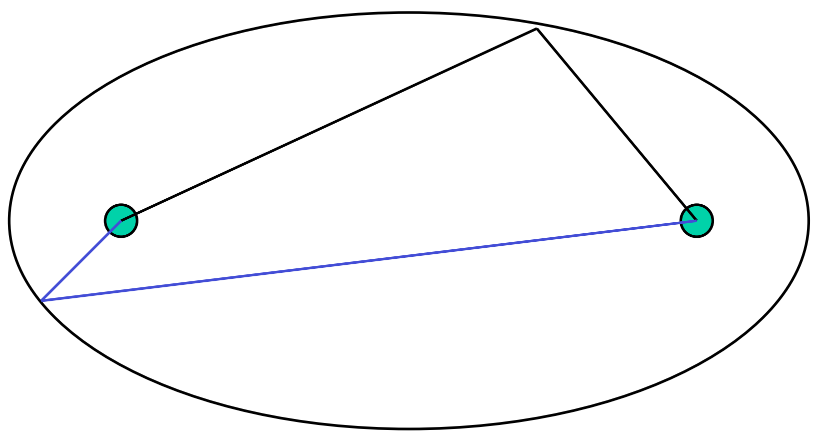
- Heliocentric parallax uses the sun as a base.
- Take a photo with telescope at two different seasons → come back to later
- Geocentric parallax uses the earth as a base.
- Make a measurement two or more times in one night.
- Use for planets → Brahe's data also had distances to planets plus position in sky

Kepler’s Laws of Motion

- Kepler figured out correct orbital shape and determined some relationships between the orbits of different planets
- A big step was realizing that Earth’s orbit about the Sun also wasn’t a circle – mostly he used relative location of Mars after repeated orbits around the Sun (Mars is close and so most accurate measurements)

Kepler's Laws of Planetary Motion (1630)

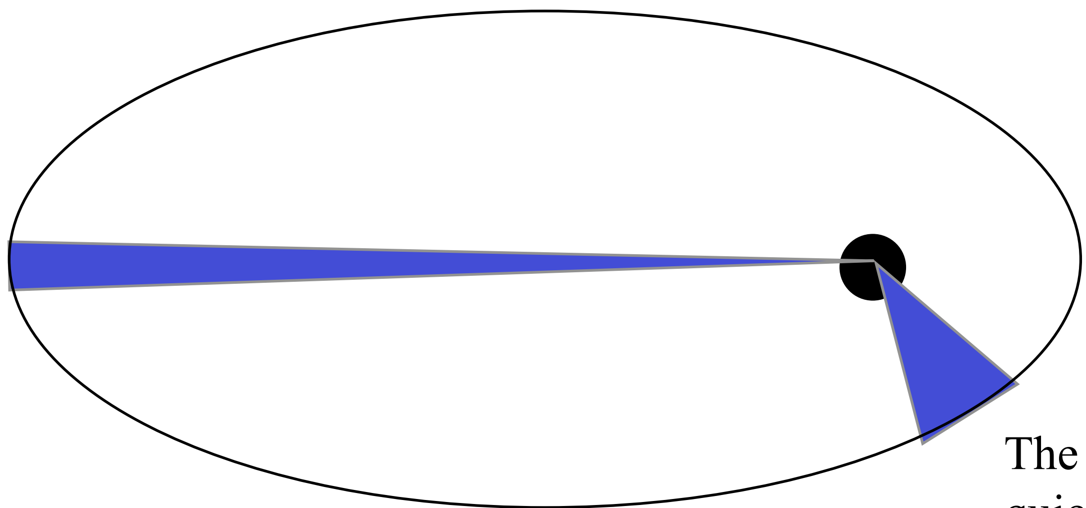
FIRST LAW: The orbit of a planet is an ellipse with the sun at one focus.



A line connecting the two foci in the ellipse always has the same length.

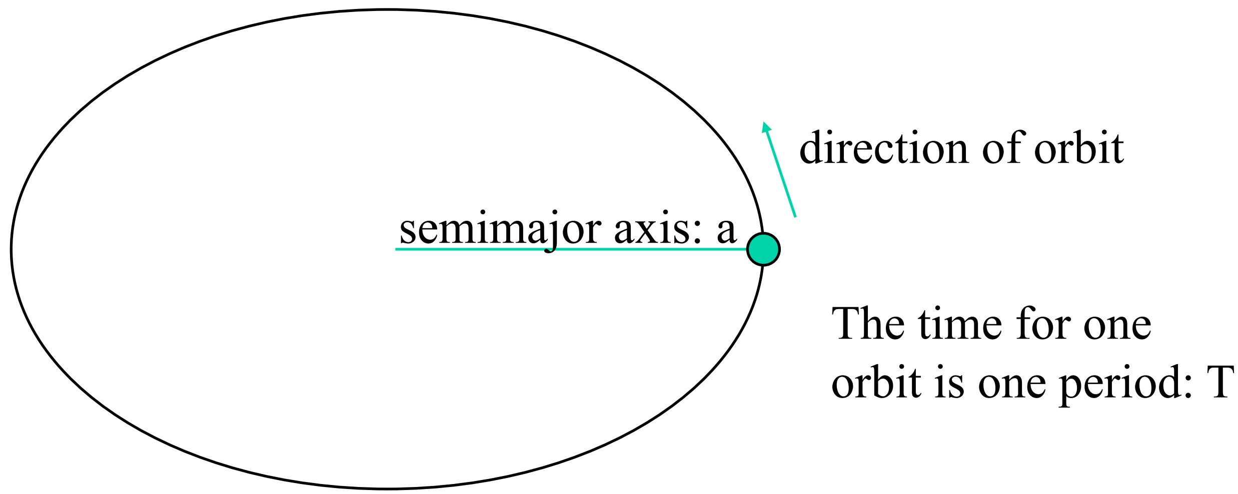
Kepler's Second Law

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



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.
- Mathematically, T^2/a^3 = constant.(=1 if use 1 Earth year and 1 AU as units), or T^2 = const X a^3.
- The constant is the same for all objects orbiting the Sun.



ics

	Mean Distance from Sun	**Sidereal Orbital Period**
	AU	P_e
Mercury	0.387	0.241
Venus	0.723	0.615
Earth	1.000	1.000
Mars	1.524	1.881
Jupiter	5.203	11.857
Saturn	9.537	29.424
Uranus	19.191	83.749
Neptune	30.069	163.727

Third Law Example

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

distance ^{3}(Jupiter-Sun) = period^2

distance = period$^{2/3}$

distance = $(11.9*11.9)^{1/3}$

distance = $(142)^{1/3}$ = 5.2 AU

- Kepler correctly determined the motion of the planets.
- 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

Newton and Kepler

- Newton's First Law of Motion:
  - A body remains at rest or moves in a straight line at a constant speed unless it is acted upon by an outside force
- Newton's Second Law of Motion:
  - If a force, F, works on a body of mass M, then the acceleration, A, is given by
  - F = M*A
- Newton's Third Law of Motion:
  - If one body exerts a force on a second body, the second body exerts an equal and opposite force on the first
- Newton's Universal Law of Gravitation
  - $F_{gravity} = G M_1 M_2 / r^2$
  - $G = 6.67 \times 10^{-11}$ meters^3 kilograms^{-1} seconds^{-2}

Newton and Kepler (2)…

- When you combine Newton's gravitation and circular acceleration, which must balance in order for the object to remain in orbit, you get a nice relation between the period, distance, and mass of the central body.
  - $F_{grav} = F_{cent}$ → equate gravitational force to centripetal force
  - $F_{grav} = G\, m_1\, m_2 / r^2$
  - $F_{cent} = m_2\, V^2 / r$
- Let the Earth be m_1 and the Moon be m_2. For **circular motion** the distance r is the semi-major axis A.
  - $V = 2\pi A / T$ → T = period of moon → $\mathbf{G\, m_1\, m_2 / A^2 = m_2\, V^2 / A}$
  - $G\, m_1 / A^2 = ((2\pi A)^2/T^2)/A$ → note that m_2's cancel!
- Rearrange to place all the A terms on the right and all the T terms on the left:
  - $G\, m_1/(4\pi^2)\, T^2 = A^3$ Looks just like **Kepler's Third Law**!
- To use A and P to solve for mass:
  - $m_1 = A^3\, (4\pi^2/G) / T^2$