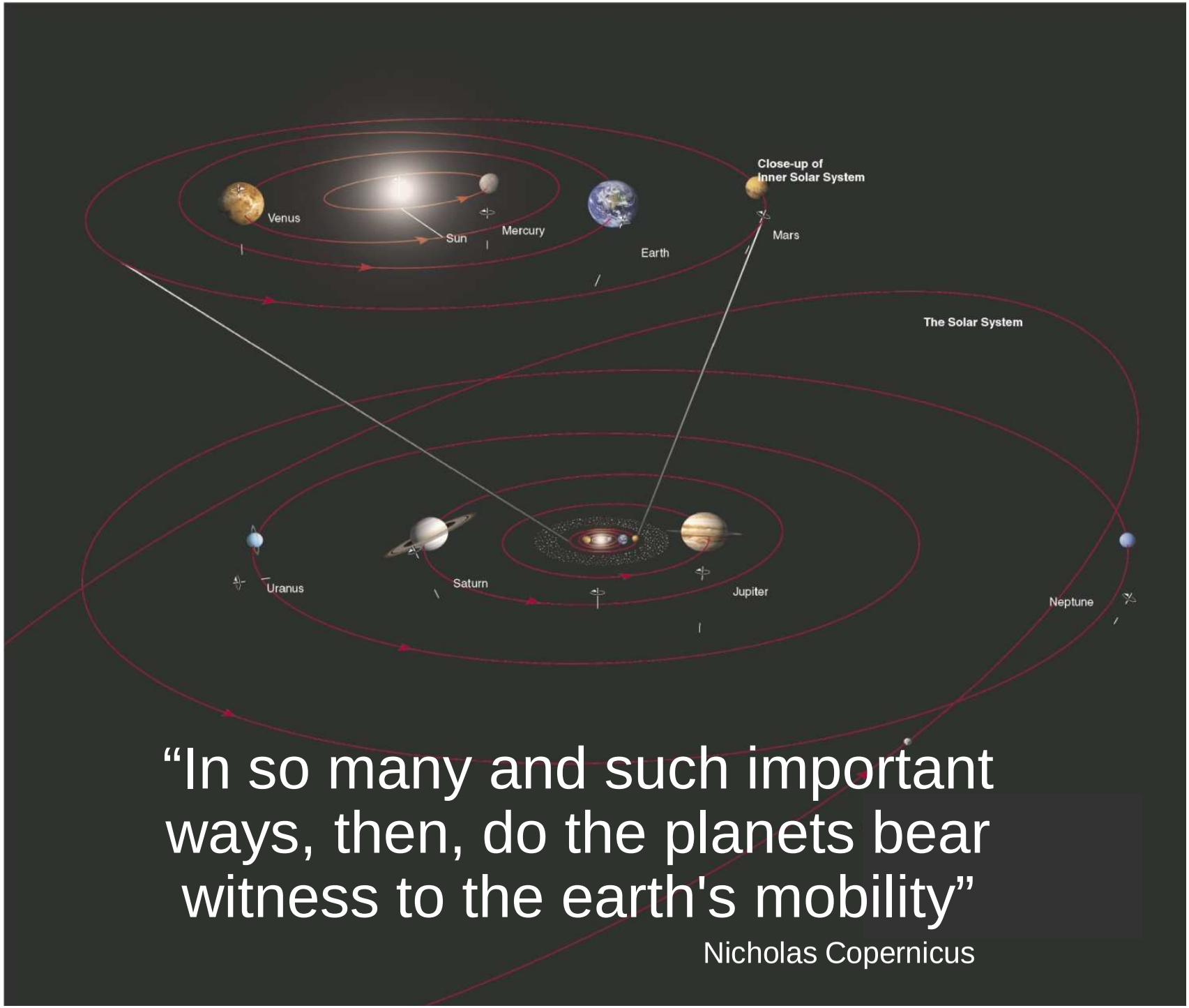


“In so many and such important ways, then, do the planets bear witness to the earth's mobility”

Nicholas Copernicus

What We Will Learn Today

- What did it take to revise an age old belief?
- What is the Copernican Revolution?
- What is the Heliocentric Model?
- What are Kepler's laws of Planetary Motion?

Problems with Geocentric Model

- Complex
  - Circles upon circles
- Not very accurate
  - Predicted planetary positions did not match observations
- But, overthrowing the Geocentric model took a lot
  - Entrenched for centuries
  - Not easy to abandon the notion that we are “special”
    - Stationary at the center of the universe

Support for a Sun-Centered Model

- Mercury & Venus are always close to the Sun on our sky
  - So, must orbit the Sun
  - Heracleides (388 – 315 BCE)
- Aristarchus (310 – 230 BCE) showed
  - Sun is larger than the Earth
  - Moon is smaller than the Earth
  - "Natural" for smaller objects to orbit larger objects
- Offered simpler explanation for apparent retrograde motion of planets

The Copernican Revolution

- Copernicus (1473 – 1543)
  - Wanted to find a better way of predicting planetary positions
  - Adopted Aristarchus' idea of placing the Sun at the center of the universe
  - Adopted circular orbits for all planets around the Sun
- Benefits
  - Simpler explanation of retrograde motion
  - Geometric relationship between planets' orbital period around the Sun and their distance from the Sun
- Problems
  - Had to add circles upon circles (orbits are *not* circular)
  - Not much more accurate than older models

The Observer: Tycho Brahe

1546 - 1601

- Dedicated his life to astronomical observations
- Built the best naked-eye observatory
- Measured positions to 1 arcmin accuracy!
  - Less than thickness of fingernail at arm's length
- Estimated distances to supernova, comets
  - Showed that they were much farther than the Moon
- Could not measure parallax to any stars
- Adopted a hybrid model
  - Earth is stationary at the center
  - Sun orbits the Earth
  - All other planets orbit the Sun

Fig 3.17

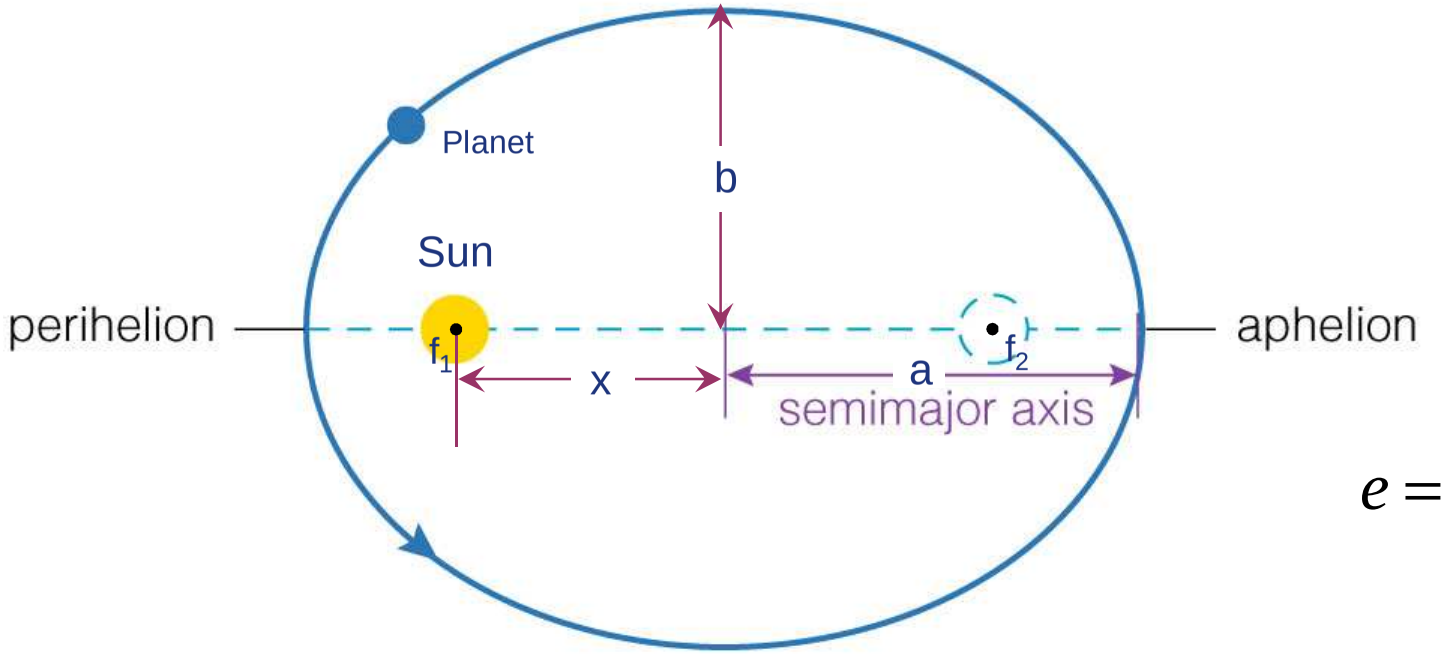
The Theoretician: Johannes Kepler

1571 - 1630

- Inherited Tycho Brahe's data
  - A lifetime of accurate data
- Worked many years to develop a circular orbit model
  - Could not accurately predict Mars' position in N-S direction
  - Some predictions differed from Tycho's observations by 8 arcmin
  - Very small difference: ¼ Moon's size
  - But 8 times Kepler's accuracy! Too big to ignore
- Led to a complete reformation in astronomy!
  - Kepler's three laws of planetary motion

Kepler's First Law

The orbit of each planet around the Sun is an ellipse with the Sun at one focus



$$e = \frac{x}{a}$$

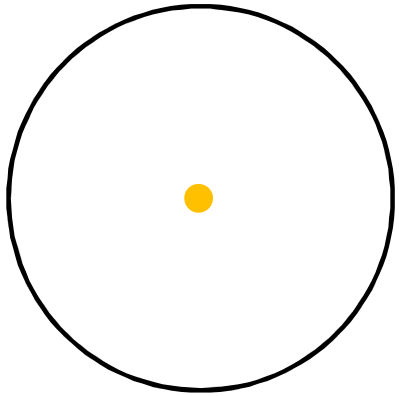
Focus (f_1, f_2): Like "center" of a circle, but have two foci

Semimajor axis (a): Like "radius", measured along long axis

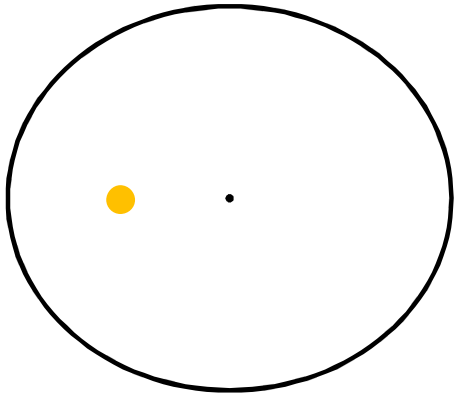
Seminor axis (b): Measured along short axis

Eccentricity (e): Measure of "elongation" (deviation from circle)

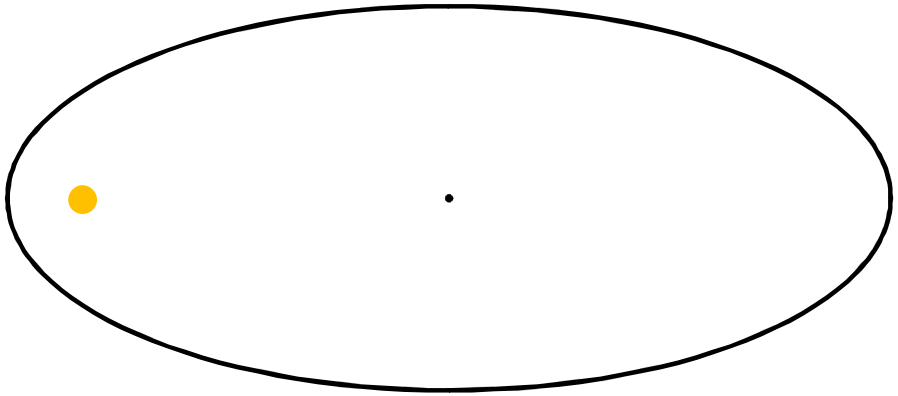
Examples of Eccentricity



e = 0 (circle)



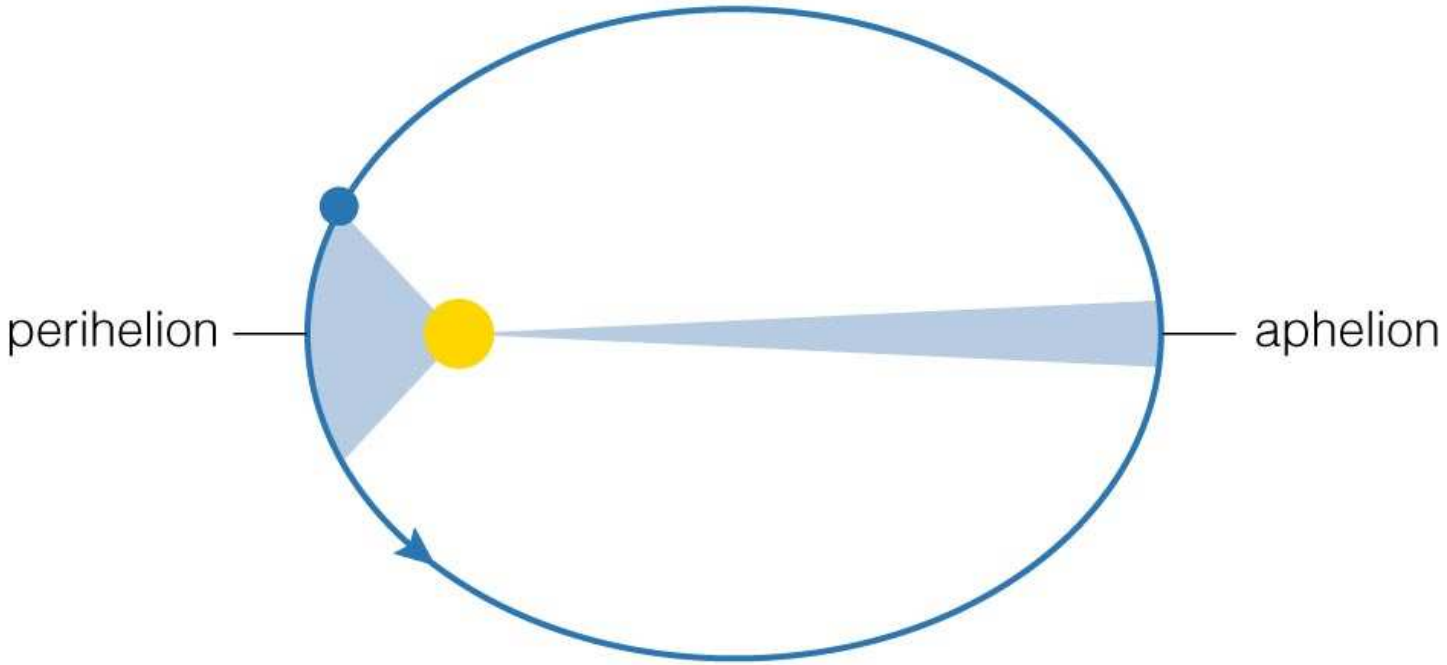
e = 0.5



e = 0.9

Kepler's Second Law

As a planet moves around its orbit, it sweeps out equal areas in equal times



- Implies that planets move faster when they are close to the Sun
  - Asteroids and comets as well

Kepler's Third Law

A planet's orbital period is related to its semimajor axis as $P^2 = a^3$

- Works only in specific units!
  - P = orbital period of planet in ***years***
  - a = semimajor axis in ***AU***
- Works only for the Solar System
- Check for Earth, P = 1 year, a = 1 AU
  - And $1^3 = 1^2 = 1$
- And for Jupiter, P = 11.86 years, a = 5.2 AU
  - $11.86^2 = 5.2^3 = 140.6$
- Implies that planets closer to the Sun move faster
  - Mercury: 49 km/s, Earth: 30 km/s, Neptune: 5.4 km/s (average speed)

Advantages of Kepler's Model

- Simple
  - No circle upon circle
- Explains *all* observations
  - Retrograde motion
  - Planetary positions
- Elegant
  - Relationship between P and a

Remaining Doubts

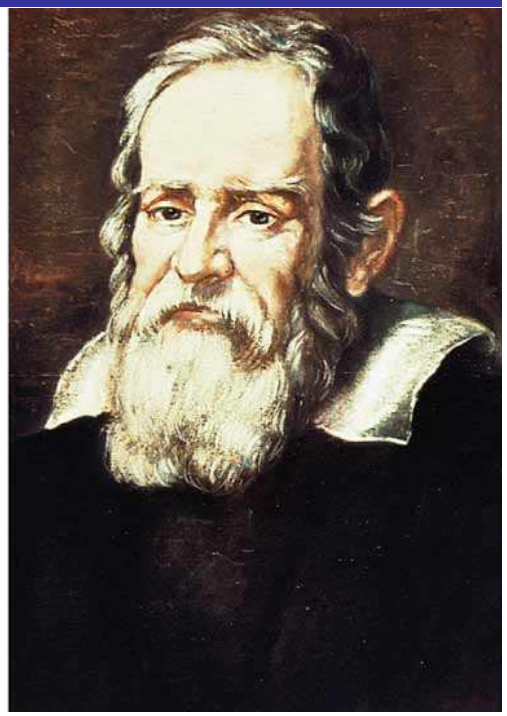
Old beliefs die hard!

Objections to Copernican Revolution:

- Earth could not be moving
  - If it were, birds & clouds would be left behind!
  - Objects tend to come to rest
- Heavens must be perfect and unchanging
  - Orbits must be circular
- Should see stellar parallax if Earth moves
  - But none measured

Galileo To the Rescue

- Studied inertia
  - Moving objects like to stay moving
- First telescope observer
  - Built his own telescope
- Observed “imperfections” in nature
  - Sunspots
  - Craters and peaks in the Moon
- Showed that there were many, many stars
  - Probably very far away, so no measurable parallax
- Observed 4 moons of Jupiter (Galilean moons)
  - Earth is *not* the center!
  - Moons will travel along with their planets and not be left behind
- Observed phases of Venus
  - Including a *full* Venus close to the Sun
  - This clinched the debate!



Galileo (1564-1642)

The Inquisition

Galileo was brought in front of a Church inquisition on June 22, 1633

- Ordered to recant his theory
- He did, fearing for his life
- But, he ultimately won
- The Church formally vindicated Galileo in 1992!