The Copernican Revolution and Kepler’s Laws

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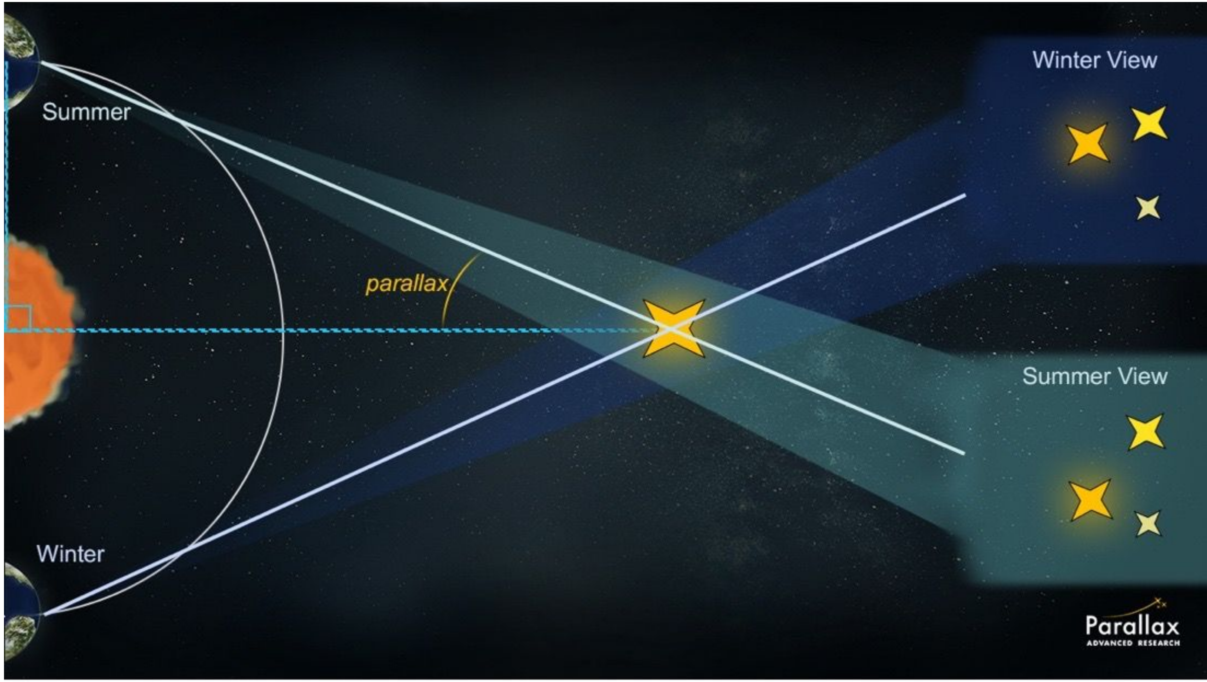
Why Did Ancient Greeks Think Earth Was the Center of the Universe? (Ptolemy)

Before telescopes, quality of human eye determined quality of data.
Human eye has angular resolution of ~1/60 of a degree.
The closest star has a parallax of ~1/3600 of a degree!

Greeks: “Either the universe is unimaginably large, or the Earth is motionless” (50/50 shot of being right!)

Some early Greek scientists **did** think the Sun was at the center of the solar system **(heliocentric)** but the data was ambiguous

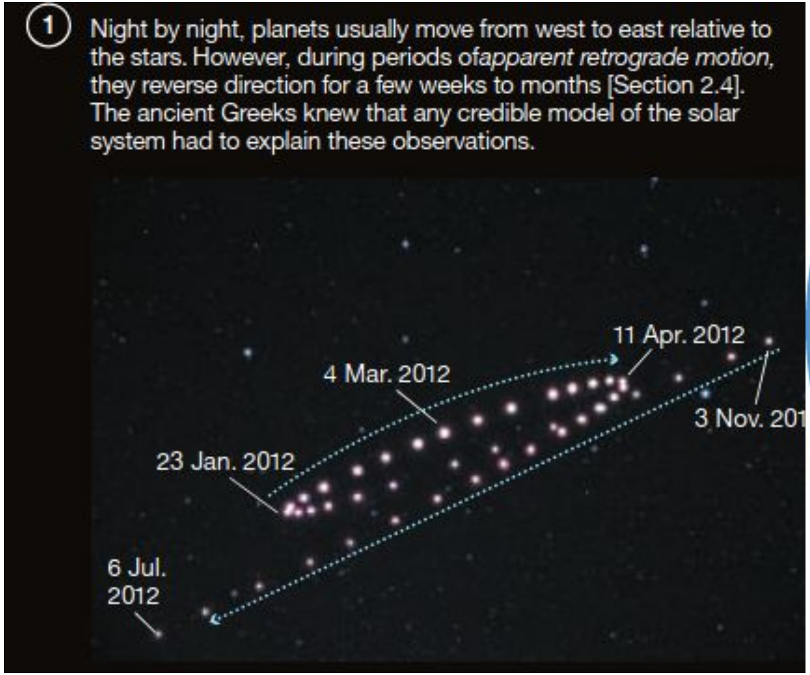


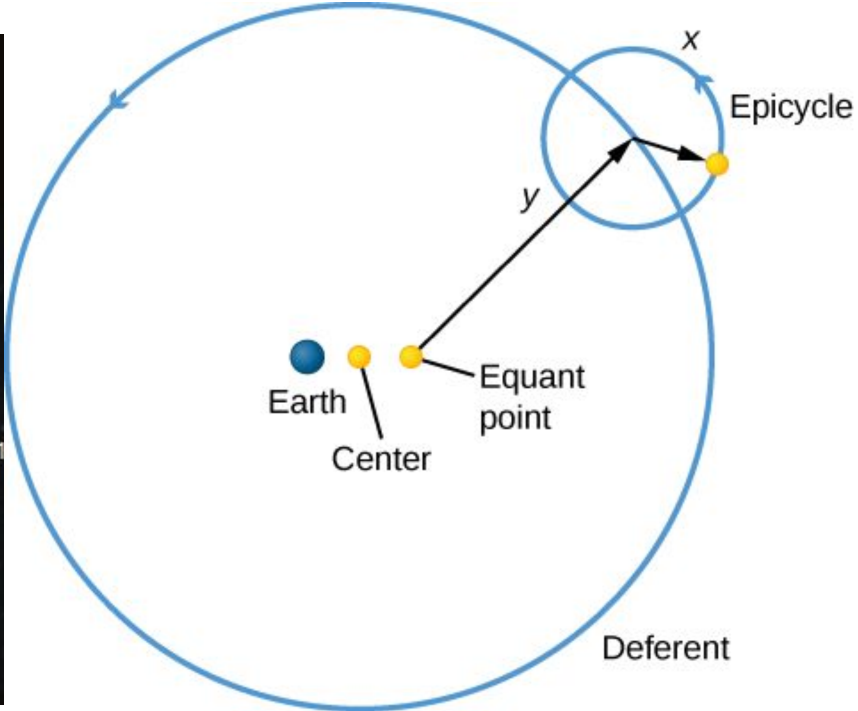
Why Did Ancient Greeks Think Earth Was the Center of the Universe? (Ptolemy)

Ptolemaic model attempts to explain observations from a **motionless Earth** assuming planets move in **perfect circles. Earth is the only planet that does not move, so Earth must be different from everything else.**

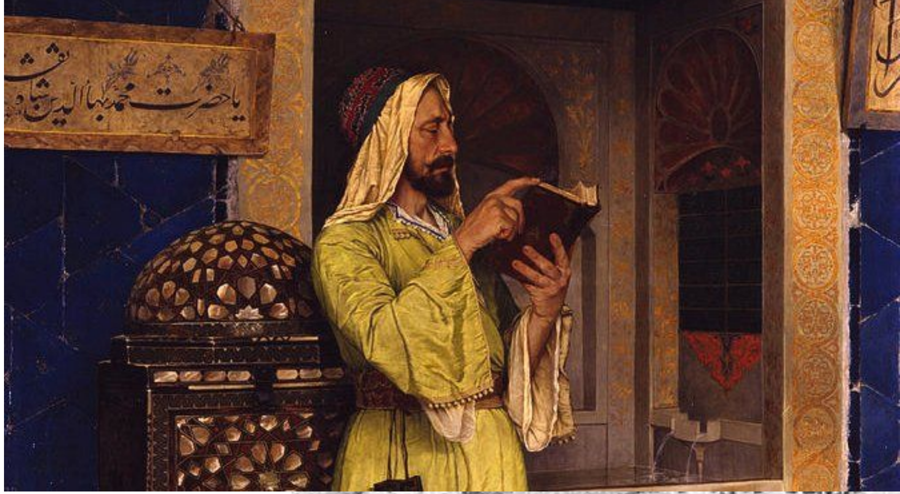
Problems: each planet had a different center for its orbit. Retrograde motion, when the planets appear to change direction, was difficult to explain without **epicycles.** As a result each planet had its own laws of motion

https://astro.unl.edu/naap/ssm/animations/ptolemaic.html

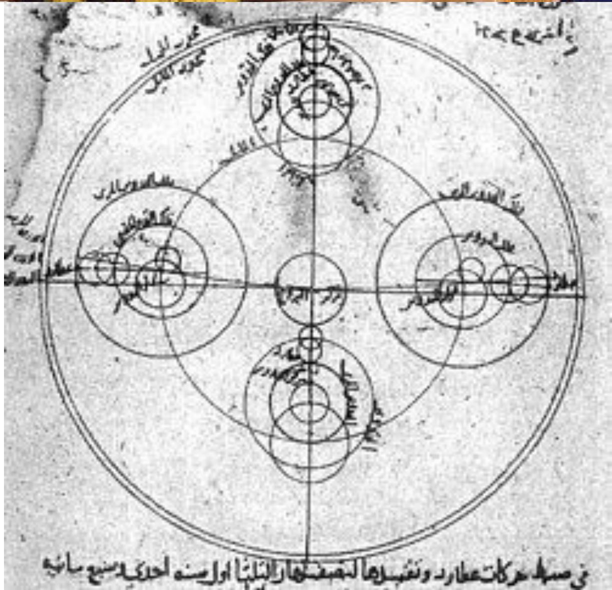




Early Objections



Ibn al-Shatir was an astronomer in the 1300s. He was a timekeeper for prayers and religious holidays, and invented many astronomical instruments to keep track of time using the sky.



He noticed the actual positions of objects deviated from Ptolemy’s model. He created a new planetary model that was significantly more accurate and gave all planets the same orbital center (the Earth), but **was still geocentric (Earth-centered).**

Mathematically similar developments to Copernicus

Copernican Revolution

- Nicoluas Copernicus noticed Ptolemys predictions “drifted”
- 1543
    - Copernicus publishes “The Revolution of the Celestial Spheres”,
    - Revolutionizes astronomy
    - Dies

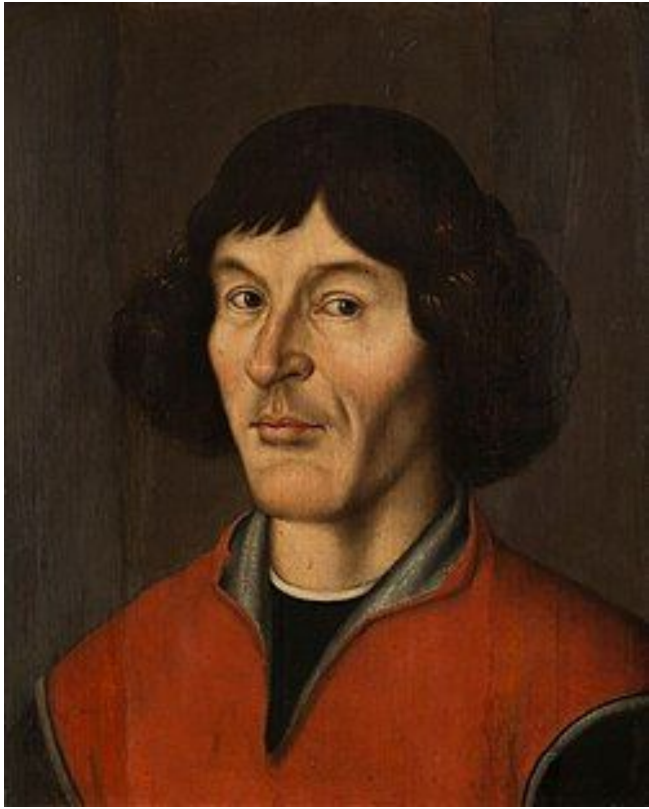
Not the first, but first to create a mathematically complete heliocentric system

Retrograde motion is **necessary** instead of a problem.

https://in-the-sky.org/imagedump/outerplanets/retrogradeMars_pause.gif

The Copernican model attempts to explain observations from an **Earth orbiting the Sun,** assuming planets move in **perfect circles.** This gave all planets the same center for the orbits, the Sun.

Problems: although the system was simpler, it was less accurate than Ptolemys!



Tycho Brahe

Astronomical data in 1600s low quality

- Naked eye observations only, and
- Data was often from multiple sources
- Different methods
- Poor documentation

Tycho Brahe

- Recorded over 30 years of data
- Never detected stellar parallax
- Was sure he would revolutionize astronomy***
- **Other planets** went around the Sun, but the Sun went around the Earth

Johannes Kepler

Johannes “ELLIPTICAL ORBITS” Kepler

- Tycho’s assistant
- **After** Tycho’s death, Kepler inherited Tycho’s data
- Developed a model of the solar system extremely similar to what we use today.
    - “Those 8 minutes of arc (<⅙ degree) pointed the road to a complete reformation of astronomy”

Kepler was (probably) the first western scientist to question the circular motion of the planets. In his model, planets move on **elliptical orbits**

The Keplerian model attempts to explain observations from an **Earth orbiting the Sun,** assuming planets move in **ellipses.** This removed the need for epicycles and gave all planets the same focus for their orbits, the Sun.

This model is both simpler and more accurate than any previous model.

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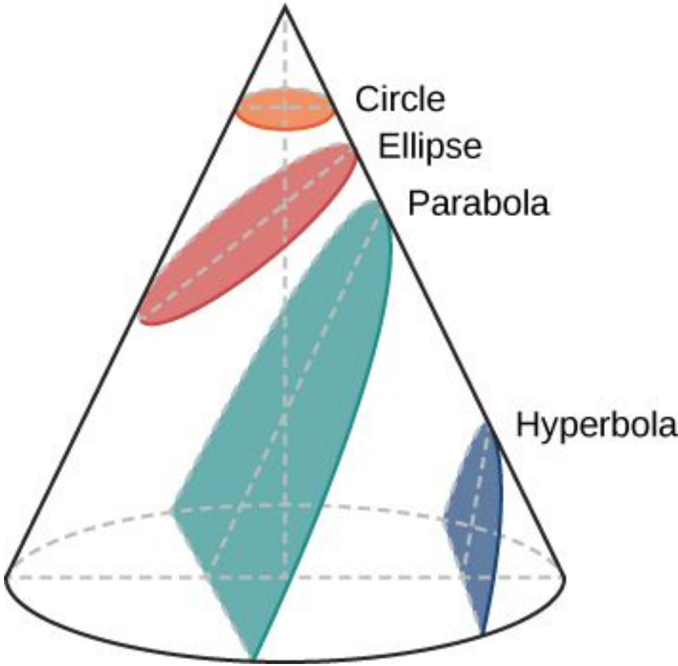


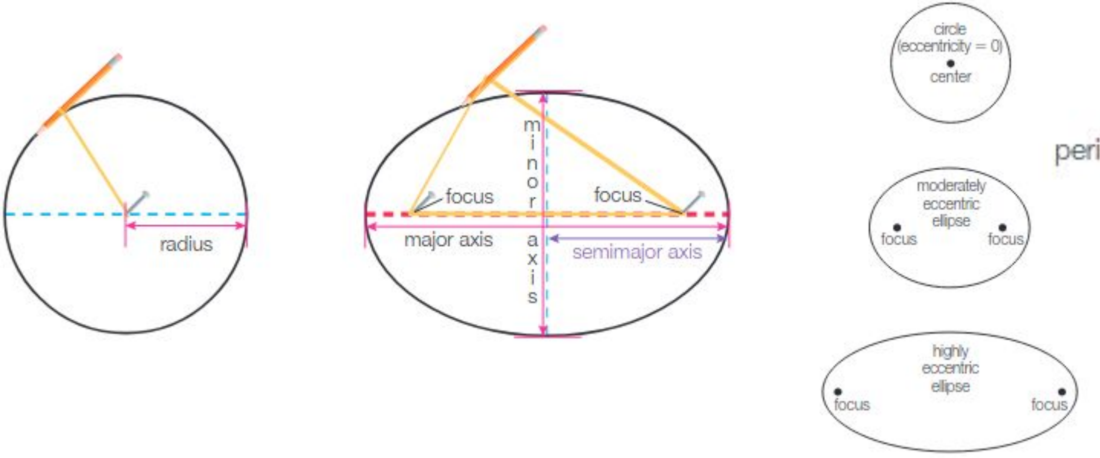
Kepler’s First Law

The motion of the planets is **described** but not **explained** by Kepler’s Laws.
https://astro.unl.edu/naap/pos/animations/kepler.html

1) **“Planets have elliptical orbits with the Sun at one focus”**

- Circle: have radius, every point same distance from the center;
- Ellipse: have semimajor axis, every point same combined distance from two foci
  - **Eccentricity** is a measure of “ovalness”.

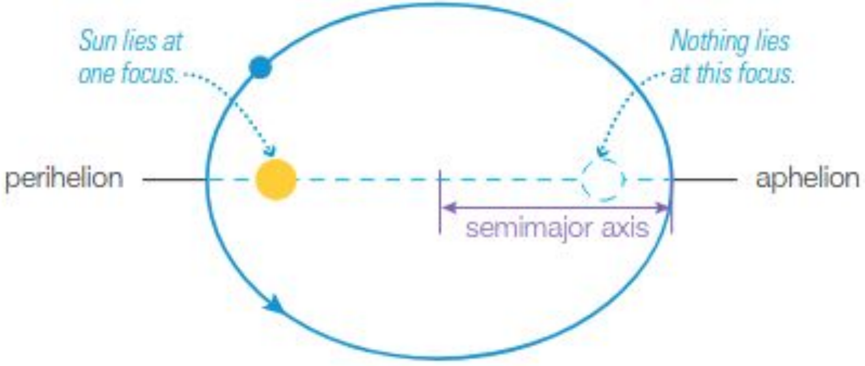
Circular orbits have e=0, constant velocity. Elliptical orbits have e>0 and **velocity that changes along the orbit**



a Drawing a circle with a string of fixed length.

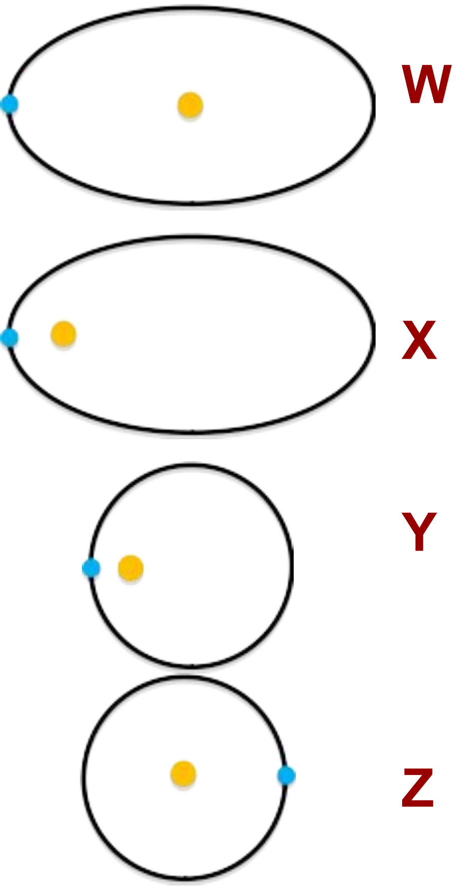
b Drawing an ellipse with a string of fixed length.

c Eccentricity describes how much an ellipse deviates from a perfect circle.



Kepler's First Law

Discussion Question: Which of these orbits is allowed by Kepler's First Law? (blue=planet, yellow=Sun)



A) All
B) W, X
C) X
D) X, Y
E) X, Z

Kepler's Second Law

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2) **"Planetary orbits sweeps out equal area in equal time"**

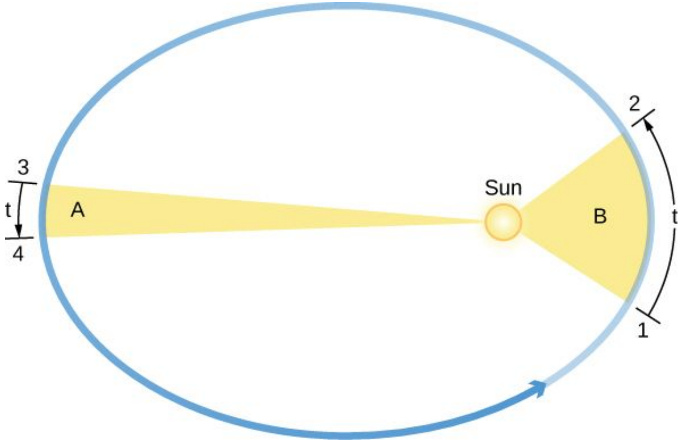
- Near the Sun (perihelion) the planet moves faster→ triangle "base" is larger near the Sun (perihelion)
- Far from the Sun (aphelion) the planet moves slower→triangle "base" is smaller far from the Sun (aphelion)

The difference in speed is due to **conservation of angular momentum**

The "base" and "height" of the triangle grow and shrink at the same rate so that the area is constant:

$$v*d=A/t=constant$$

Discussion Question:
When the planet is at aphelion (furthest from the Sun) it is a distance d from the Sun with orbital speed v.
When the planet is at perihelion (closest to the Sun) it has speed 3v.
What is the distance to the Sun at perihelion in terms of d?



Kepler's Third Law

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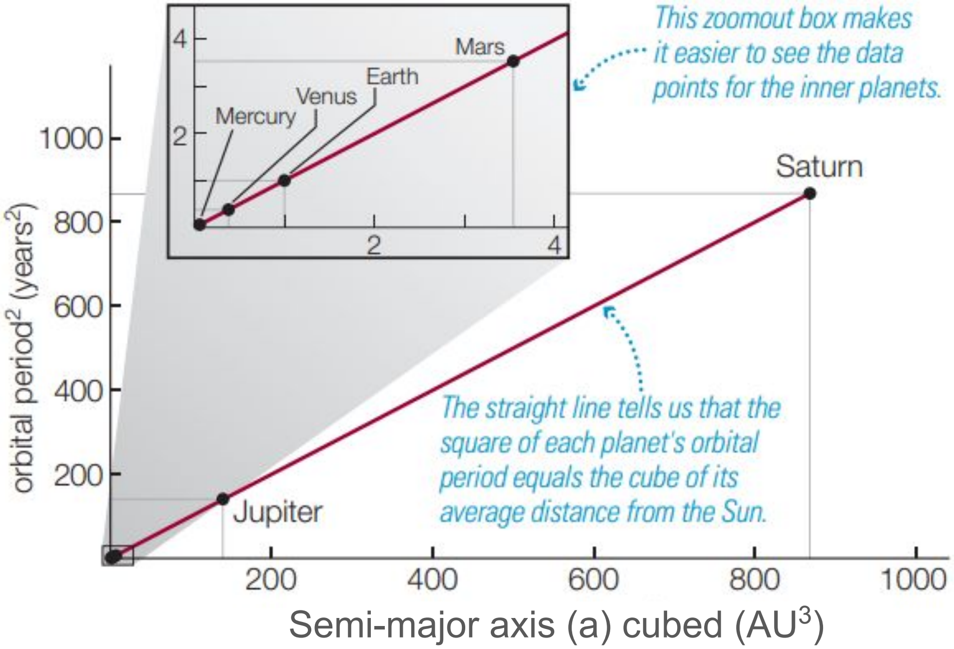
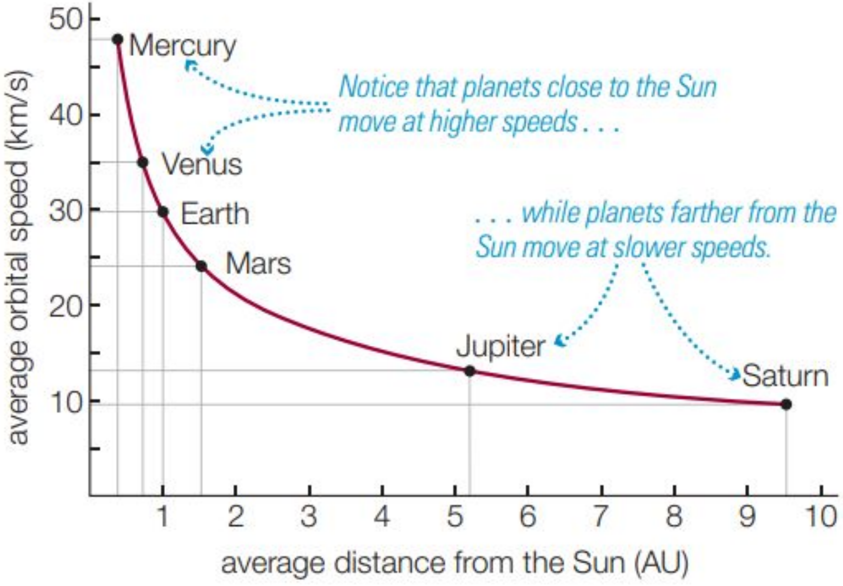
3) **$P^2 \propto a^3$ "The period of a planet squared is proportional to the length of the semimajor axis cubed"**
($P^2=a^3$ **only** if using units of AU and years!)

If planets travelled the same speed, we would have P=a, since further planets travel a larger distance around the Sun. But $P^2=a^3$, so the planets also have lower average speed at higher radius.





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Discussion Question: What is the length of a year on Neptune, which has a semimajor axis of 30AU?

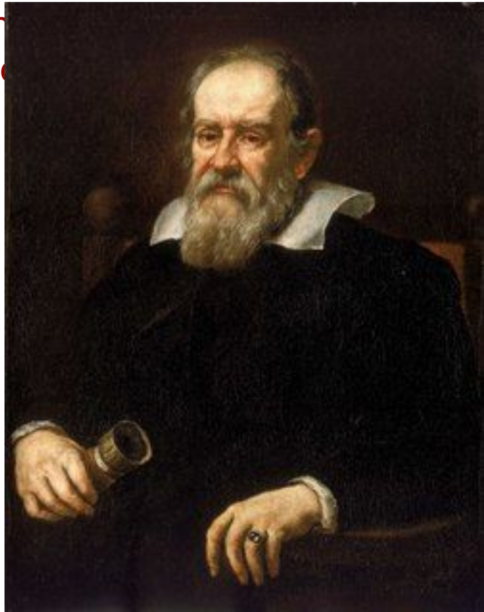
Aftermath of Kepler’s Laws; Galileo’s Observations

The Copernican Revolution

- Beginning: full (but incorrect) description of a heliocentric solar system by Copernicus.
- Middle: full (and correct**) description of a heliocentric solar system by Kepler
- End: Galileo and Newton (no time for Newton today)

Galileo helped settle many objections to heliocentrism:

1) If the Earth is moving, why are we not left behind?
2) **Still** no stellar parallax, which we should see if the Earth orbits the Sun! (and if th
3) Various semi-religious/traditionalist objections; the motions and faces of the plan perfect and unchanging. Instead, Kepler suggests their motion is lopsided and always in flux.



The work of Copernicus, Tycho, and Kepler was mostly mathematical.
Galileo provided many explanations and observations that helped answer the remaining questions

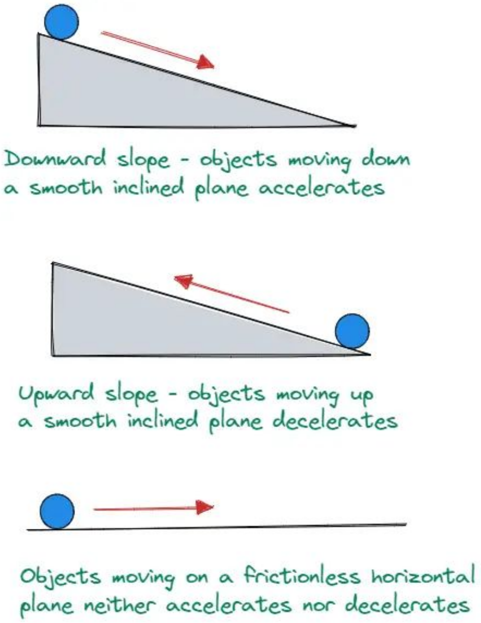
Aftermath of Kepler's Laws; Galileo's Observations

Galileo developed and used a better telescope. He used it to settle objections to the heliocentric model:

1) If the Earth is moving, why are we not left behind?

Galileo performed controlled experiments using friction, and showed that an object in motion will stay in motion unless something influences it. Once on Earth, moving around the Sun the same as the Earth, there's no reason things would fall off of it (even without gravity).

2) **Still** no stellar parallax, which we should see if the Earth orbits the Sun!



Telescopes were still not good enough to detect stellar parallax.

Galileo used his telescope to show "haze" of Milky Way is made of stars→ suggests parallax not visible to eye

Aftermath of Kepler's Laws; Galileo's Observations

Galileo developed and used a better telescope. He used it to settle objections to the heliocentric model:

3) Various semi-religious/traditionalist/cultural objections; the motions and faces of the planets were thought to be perfect and unchanging. Instead, Kepler suggests their motion is lopsided and always in flux.

Galileo used his telescope to view the surface of the Moon and Sun in more detail than ever before. Discovers:

- "Imperfections" on surface of Sun and Moon
- Moons of Jupiter, the first observation of something orbiting **neither the Sun or Earth.**

Now astronomers believe in (and overwhelming evidence supports) the Copernican Principle: Earth does not occupy a special place in the stars.