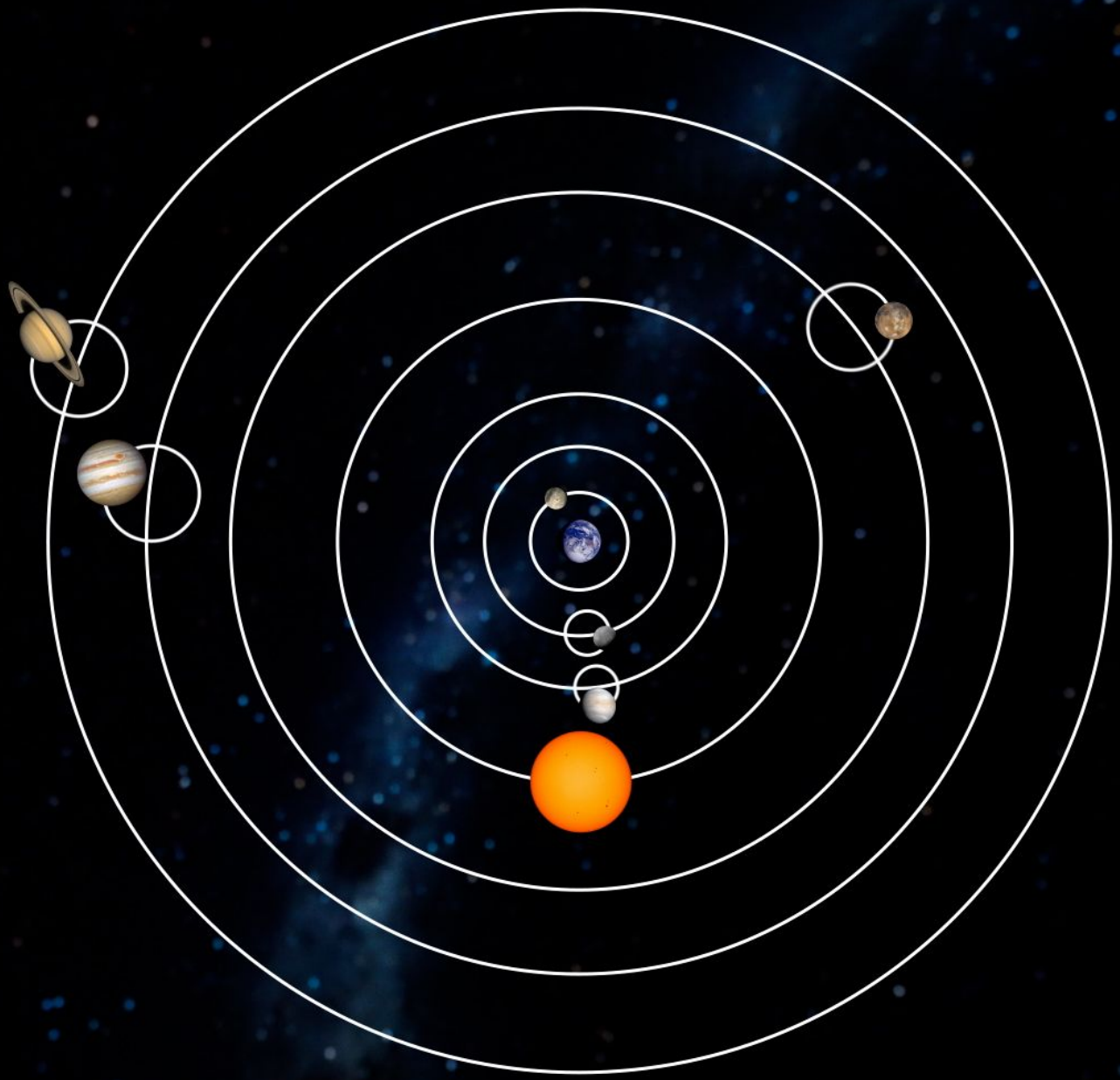
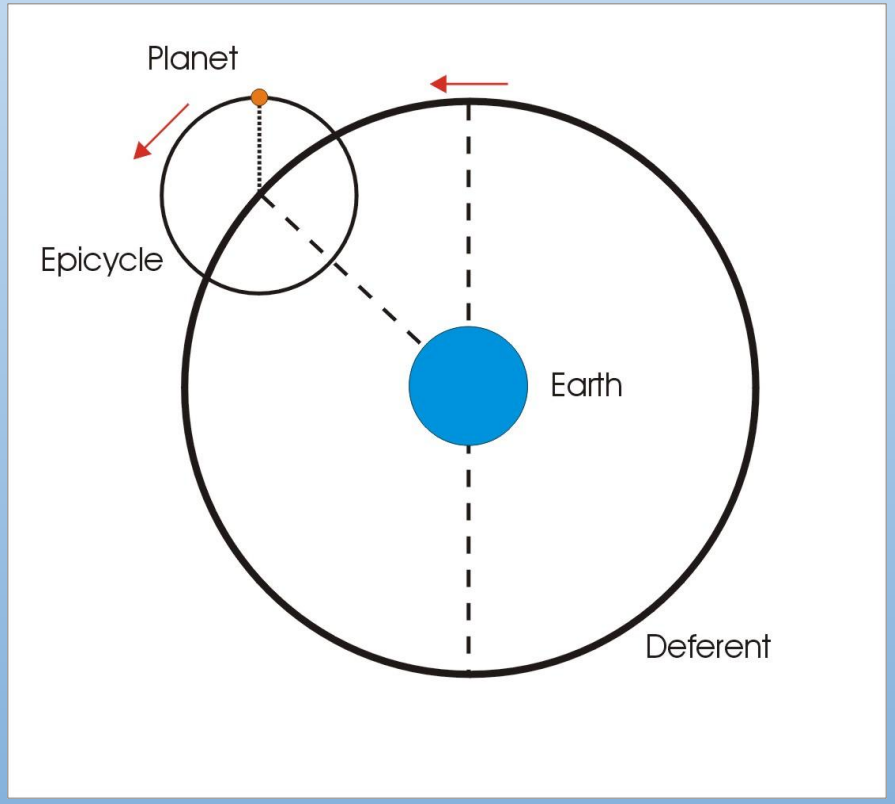
Ptolemy
of Alexandria

150 CE

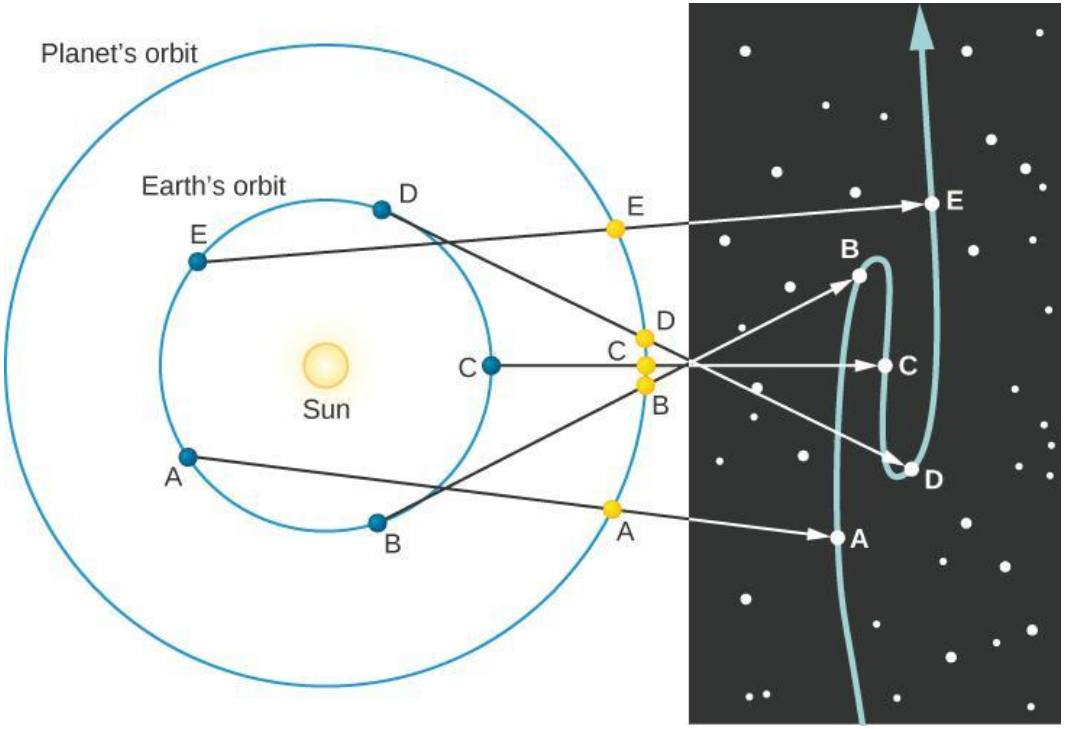


Epicycles and Deferents

- Ptolemy's system for each planet involves a large (imaginary) circle around the Earth, called the ***deferent***, on which revolves a smaller circle, the ***epicycle***.
- The visible planet sits on the edge of the epicycle.
- Both deferent and epicycle revolve in the same direction.



Ptolemy's Model (authority for over 1000 years)

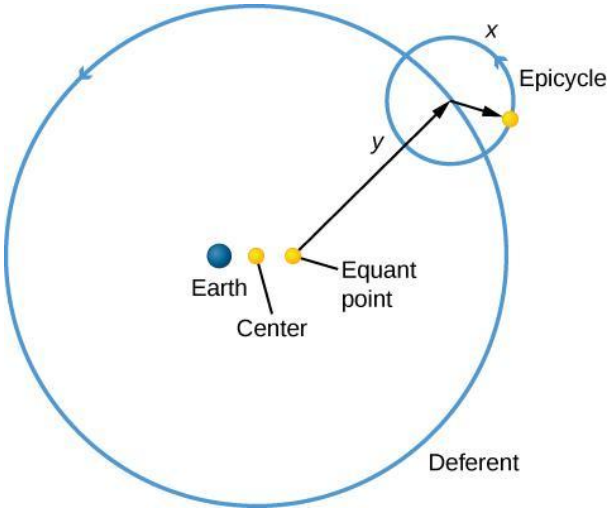


Some of the known planets seem to move **backwards** through the sky. This is called **retrograde motion**, and it occurs when we "catch up and pass" a slower planet.

Planetary Motion Simulator

Ptolemy's Model (authority for over 1000 years)

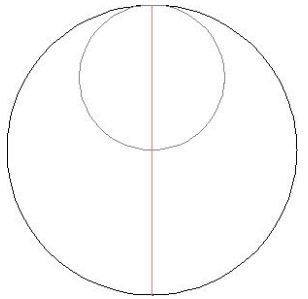
The way to deal with this motion in a geocentric idea was to create additional circles. **Ptolemy** added these circles, called **epicycles**.

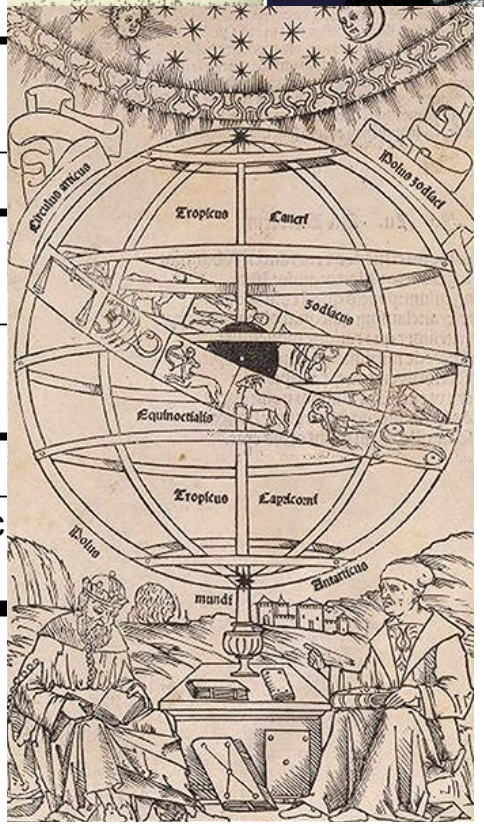


Ptolemy's epicycles were "circles on circles." This model lasted for 1000 years and was eventually accepted as authoritative (unquestionable truth) in Christian Europe.

Ptolemaic Simulation

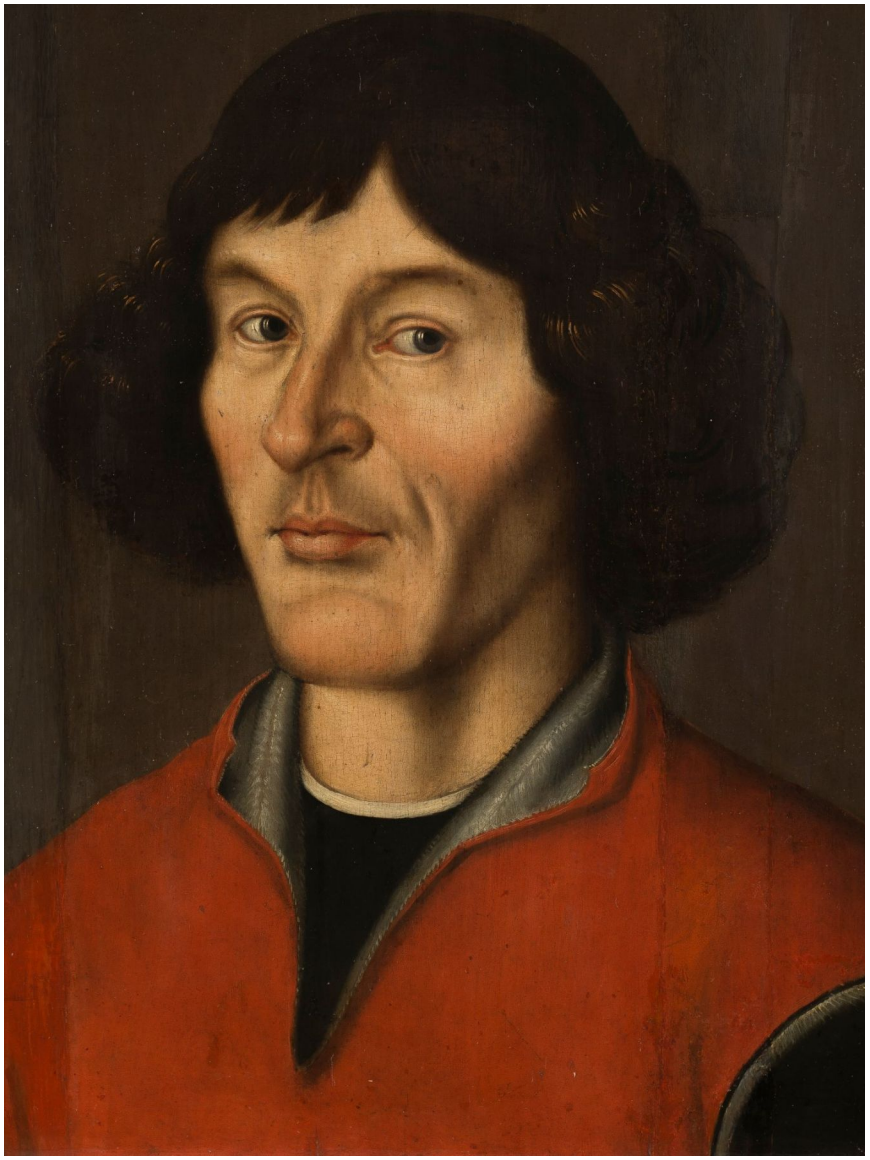
Period	Key Development	People and Contribution
c. 150 CE	Synthesis	Ptolemy
		Geocentric model codified in the *Almagest*.
9th-13th C.	Islamic Golden Era: Preservation & Critique	Al-Battani, Ibn al-Haytham, Al-Tusi, Ibn al-Shatir
		Refined data, criticized physical models, created new devices (Tusi-couple).
12th-13th C.	Translation	European Translators
		Ptolemy's **refined work** returned to Europe via Latin.
15th Century	Renewed Scrutiny	Peuerbach & Regiomontanus
		Produced mathematical and widely read textbook critique of the *Almagest*.
1543	Revolution	Nicolaus Copernicus
		Published *De revolutionibus*, proposing a heliocentric universe and igniting the Scientific Revolution.





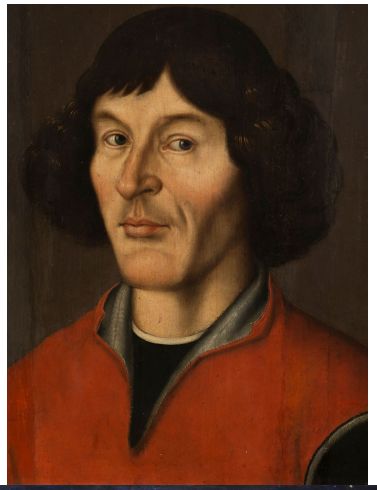
Copernicus (1473-1543)

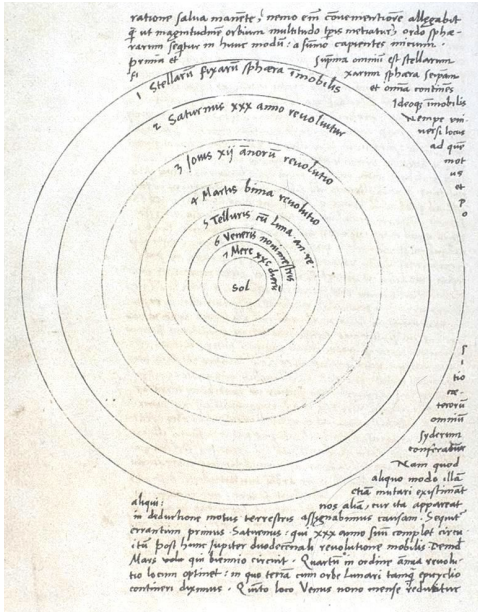
- Polish doctor, lawyer, mathematician, and amateur astronomer
- Sought simpler model
- Solution: Heliocentric – or sun-centered – model, but the model lacked evidence
- Published outline of ideas first in 1514 ("Little Commentary")



The Path to Revolution: Copernicus

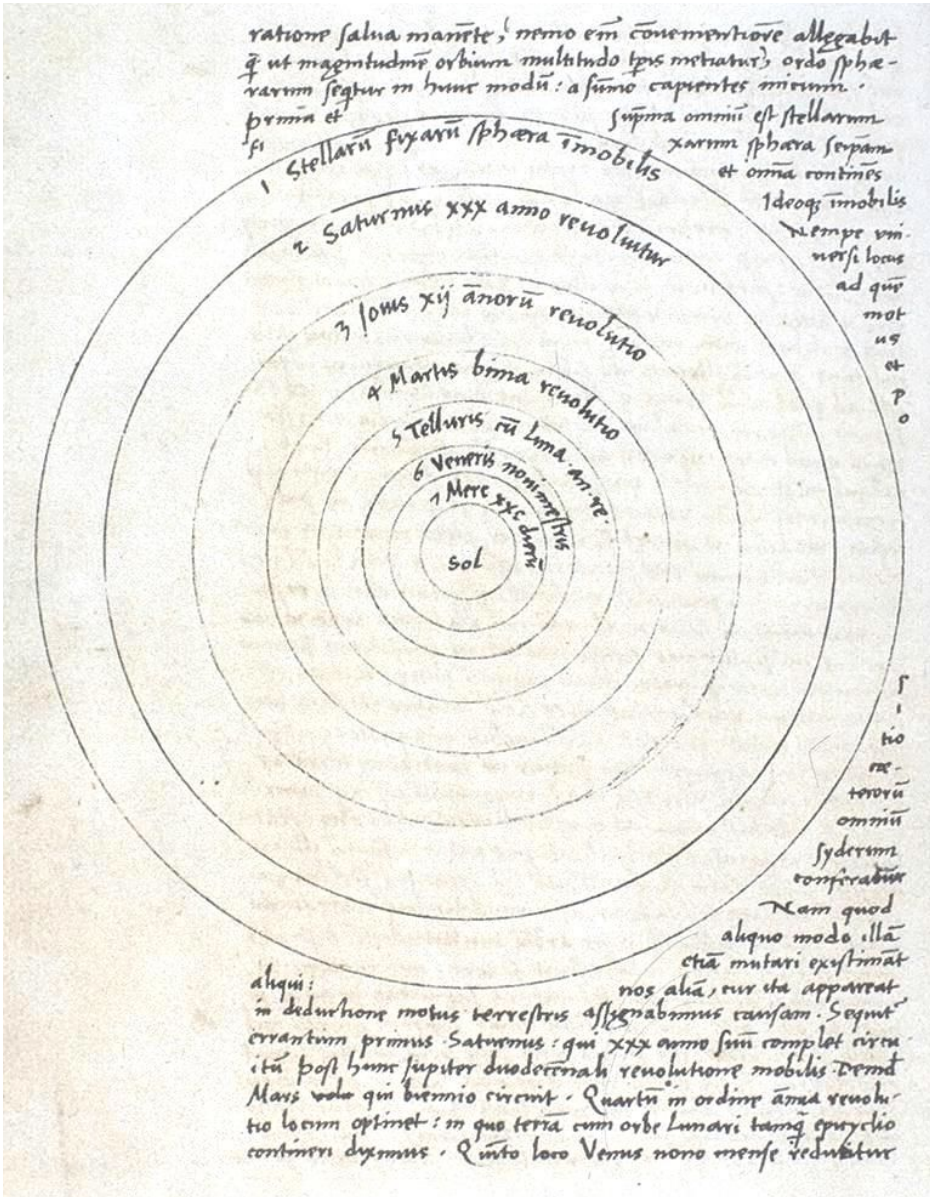
- Published heliocentric model in *De revolutionibus orbium coelestium* (On the Revolutions of the Heavenly Spheres)





***Astronomer Copernicus, or Conversations with God* by Jan Matejko (1873)**

The Path to Revolution: Copernicus



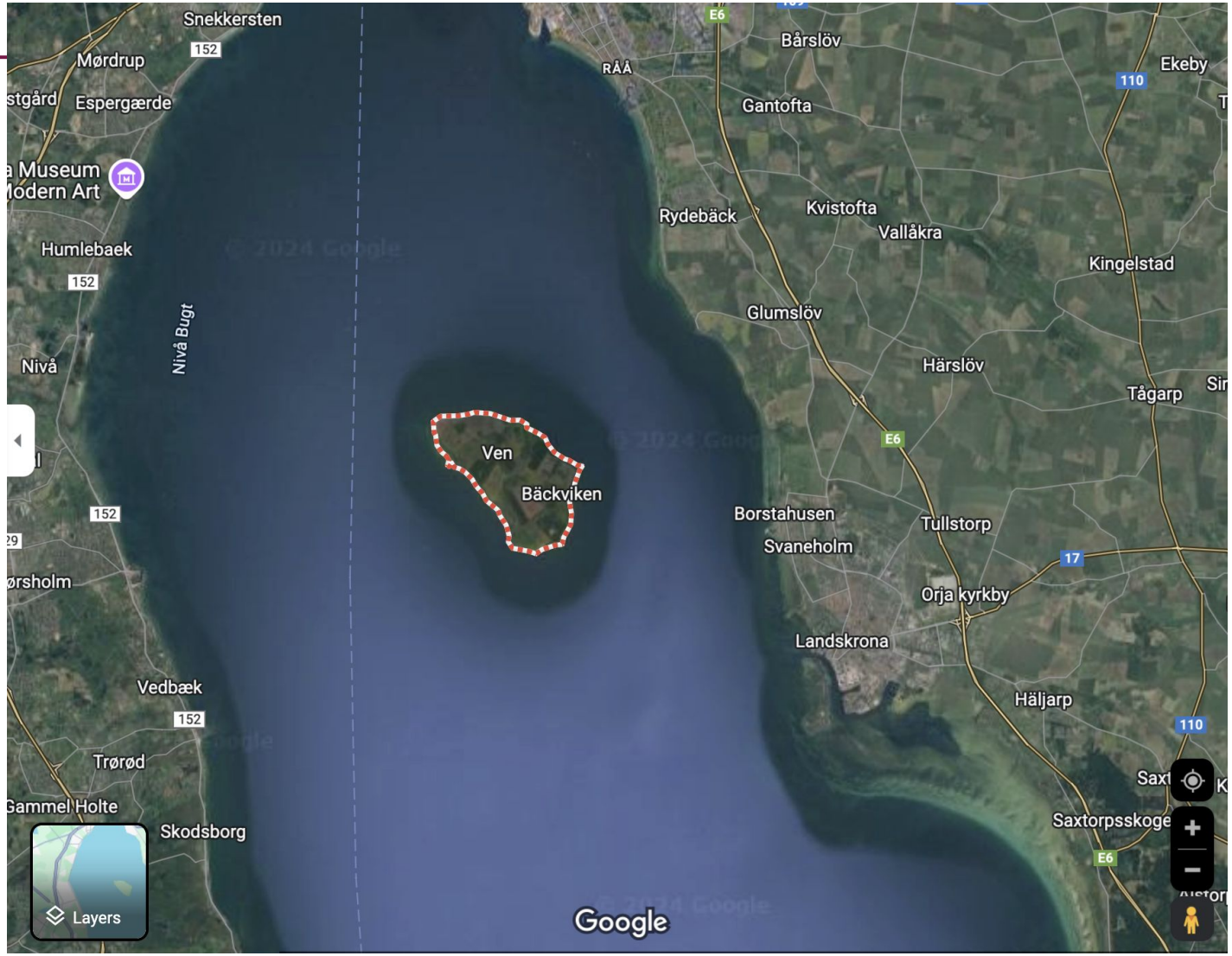
***Astronomer Copernicus, or Conversations with God* by Jan Matejko (1873)**

Tycho Brahe

Danish nobleman was surveying the sky, without a telescope.

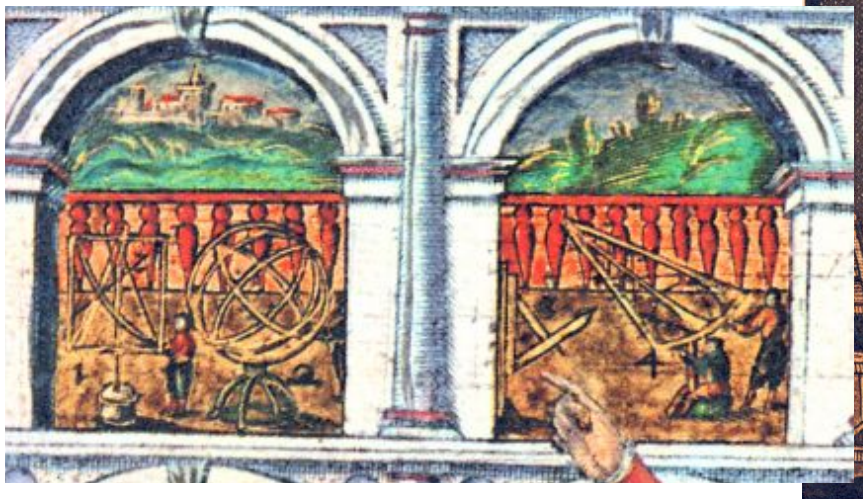
Tycho Brahe

Observatory and highly accurate instruments no his own island, Hven.



Tycho Brahe

After observing a supernova (Tycho's Star) in 1572, he was given funds for an observatory and highly accurate instruments no his own island, Hven.



Tycho Brahe

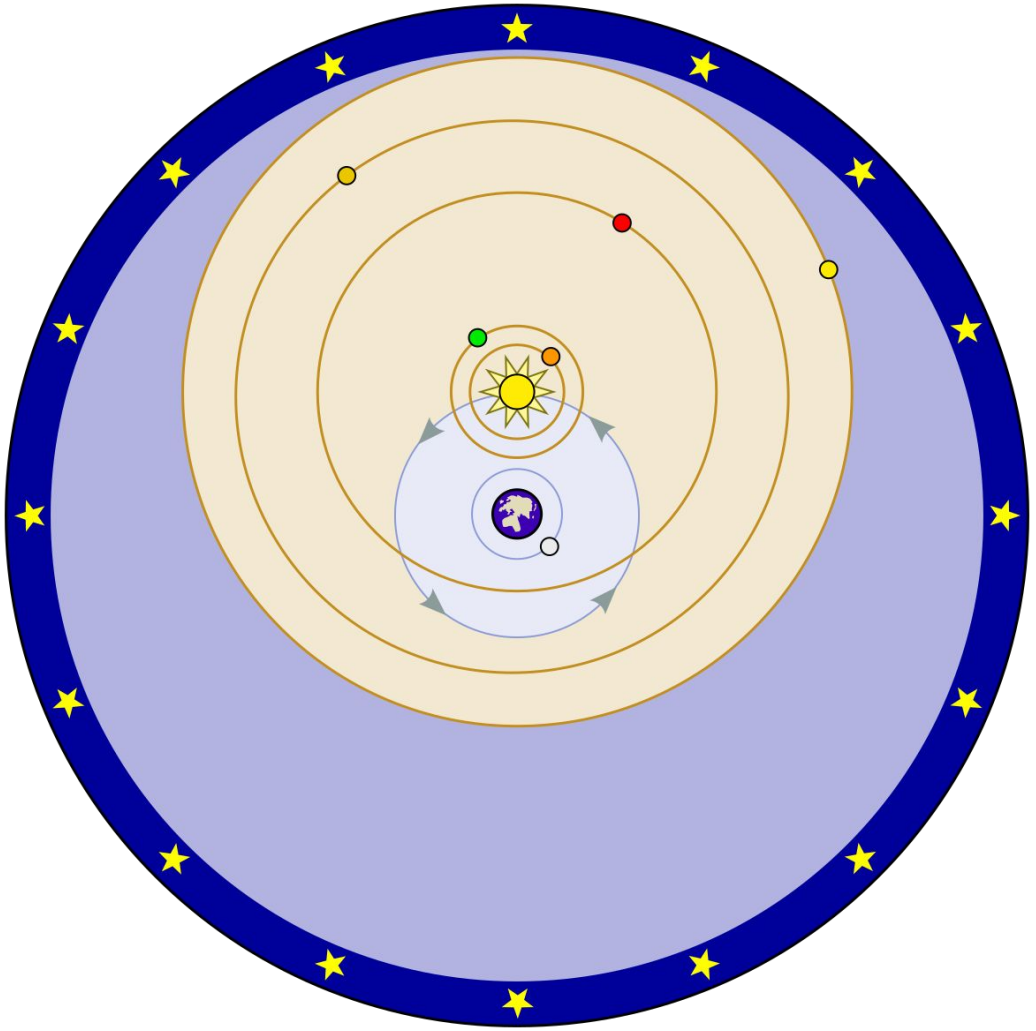
Alchemy!

Not as well known of Brahe:

16 furnaces in basement, lots of equipment for distillations and purifications

Tycho Brahe's Geoheliocentrism Model of the Solar System

- A geo-heliocentric system for the solar system
- Earth is stationary at the center
- The Sun and Moon revolve around the Earth
- The other planets (Mercury, Venus, Mars, Jupiter, Saturn) revolve around the Sun
- A hybrid of the Ptolemaic and Copernican systems, was a compromise that allowed for the planets' observed motions
- While conceptually different, the Tychonic model is mathematically equivalent to the heliocentric Copernican system

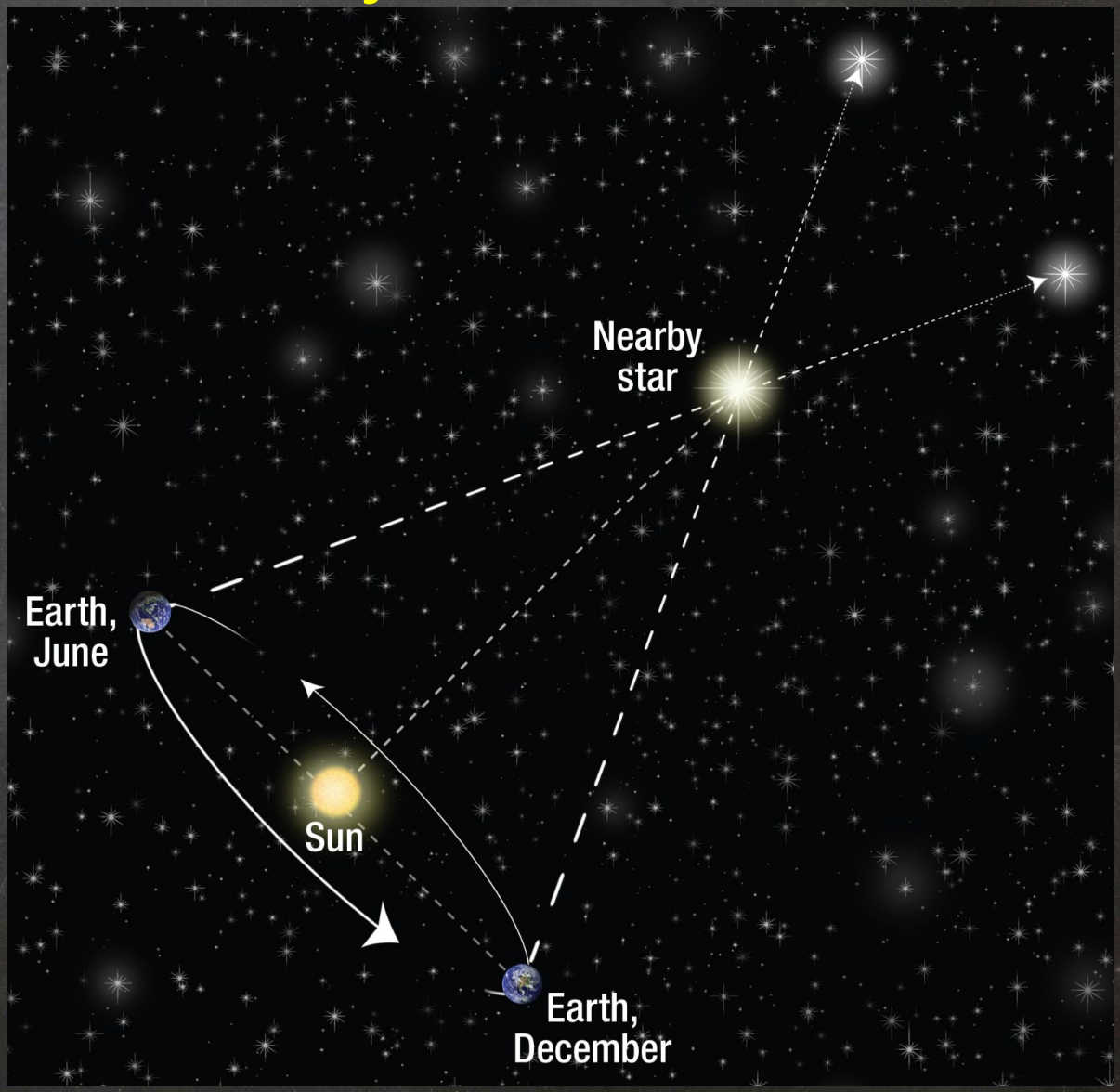


Grab a Sheet of Paper, Close your Computer and Put Away Your Devices …

Tycho made his hybrid model because he did not see any evidence of Stellar Parallax.

Handwrite your answer to this question:

Speculate on what was Copernicus' answer to the problem of Stellar Parallax?

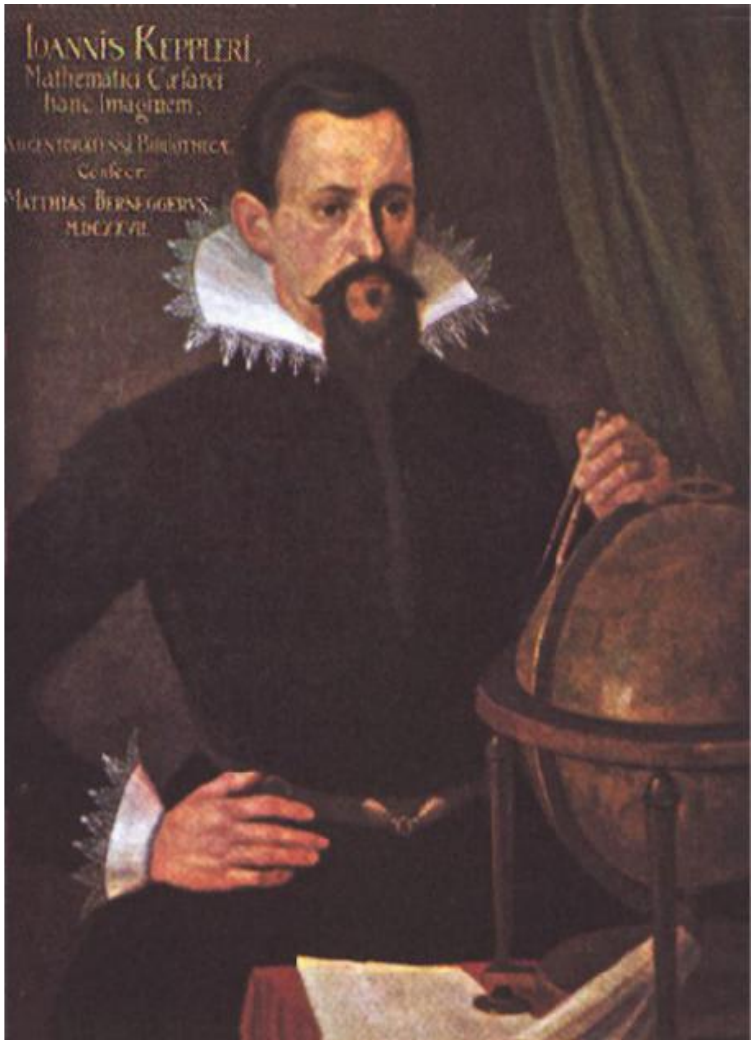


Tycho Brahe and Johannes Kepler

Brahe was exceptionally good at gathering data, but his interests did not include the difficult mathematical analysis of observations.

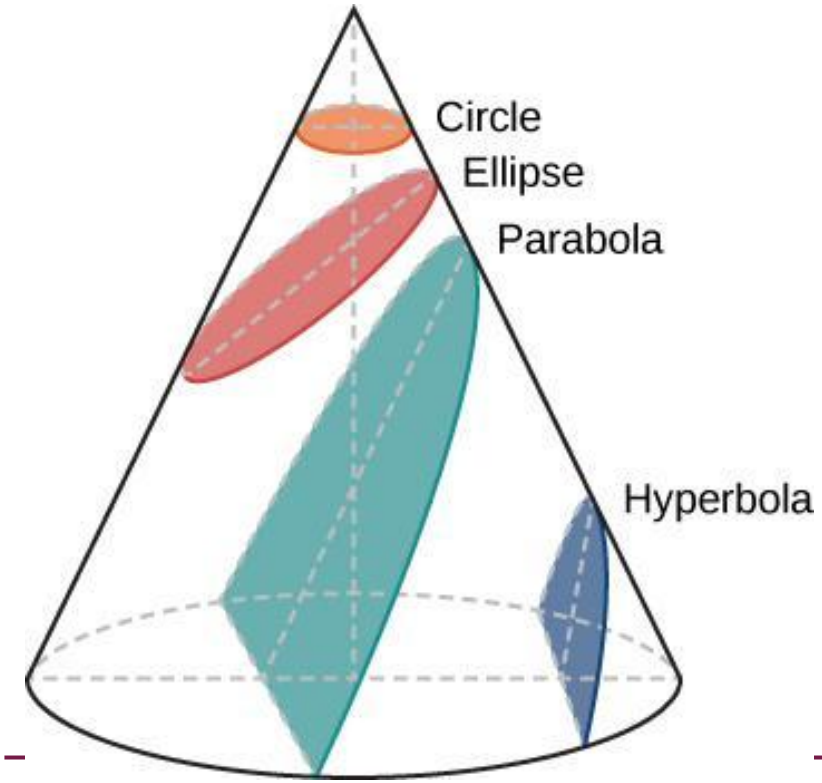
Brahe hired Johannes Kepler as an assistant, but kept most data to himself. Only after Brahe died was Kepler able to do a full mathematical analysis on the orbits of the planets.

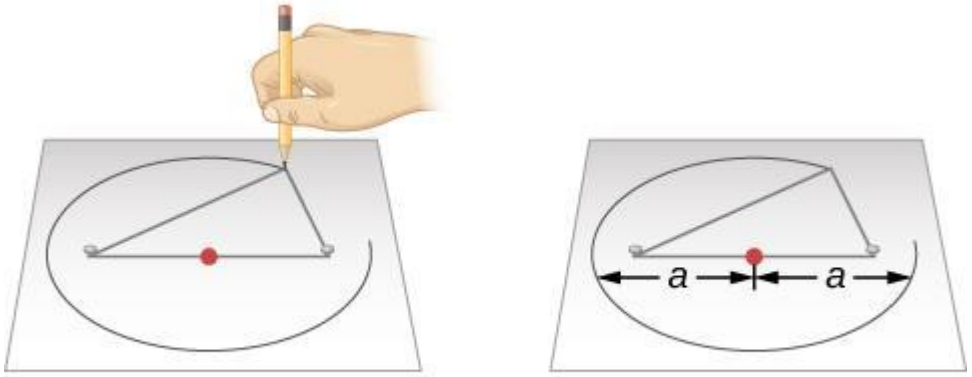
Kepler's analysis led to his **three laws of planetary motion**.



Kepler's Laws of Planetary Motion

Since Kepler determined circles could not fit the orbital data, he tried a different "conic section" shape, called an **ellipse**.





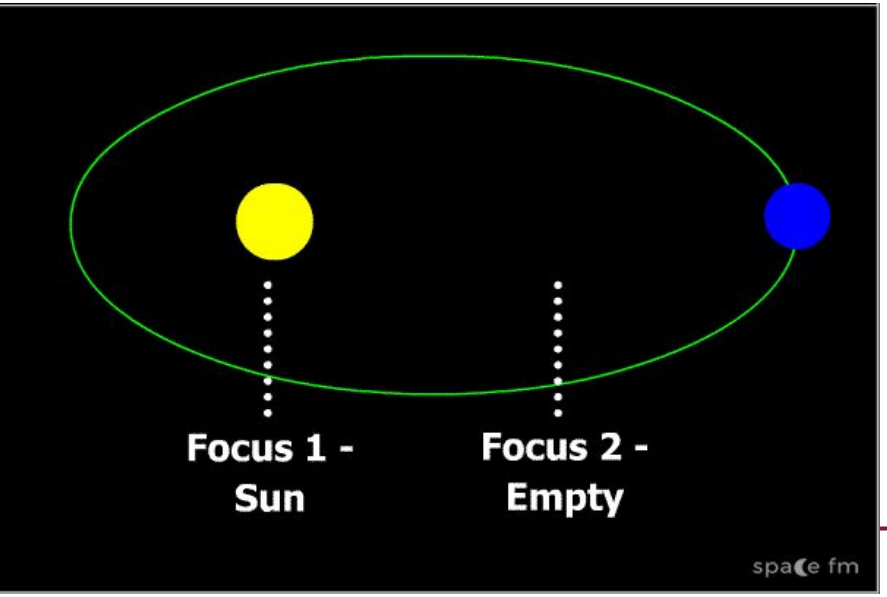
(a) (b)

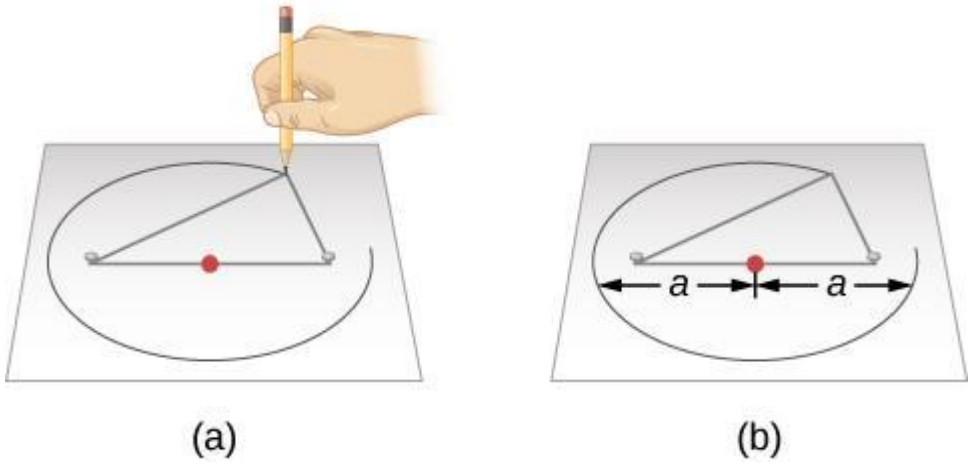
Kepler's First Law

Unlike a circle, an ellipse is not defined by a single central point, but rather two **foci** (singular: focus).

The planet to Sun distance is always changing

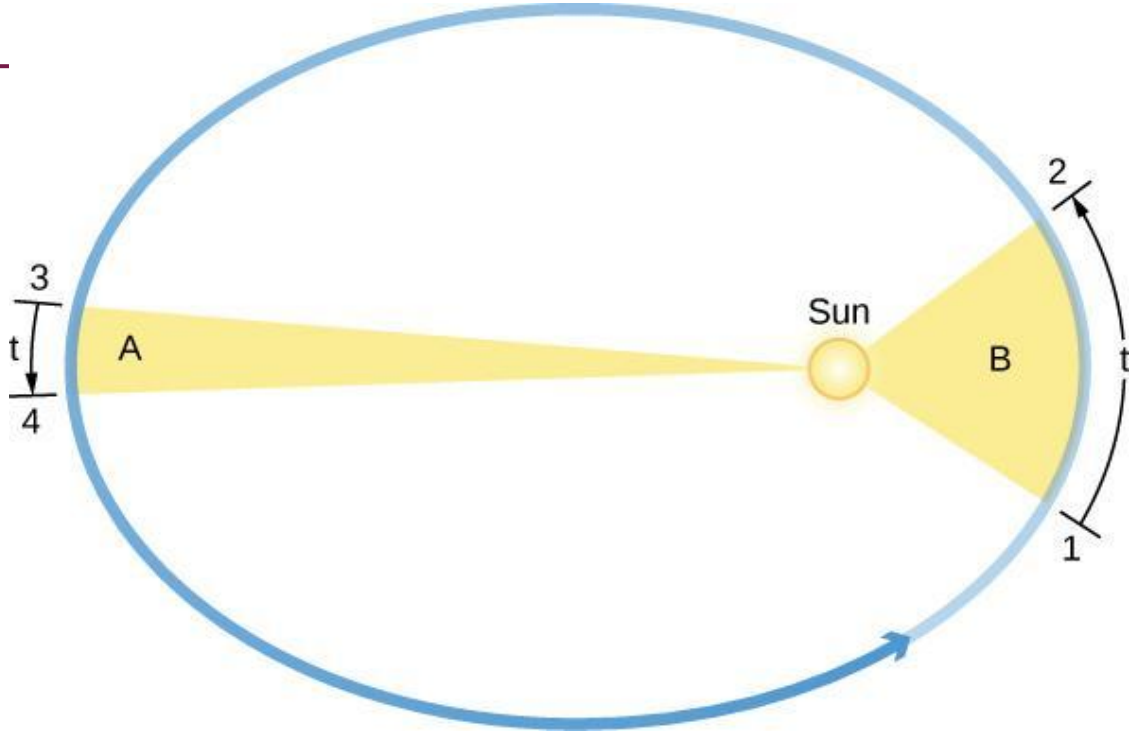
Kepler's First Law states that each planet moves around the Sun in an orbit that is an ellipse, with the Sun at one **focus** of the ellipse.

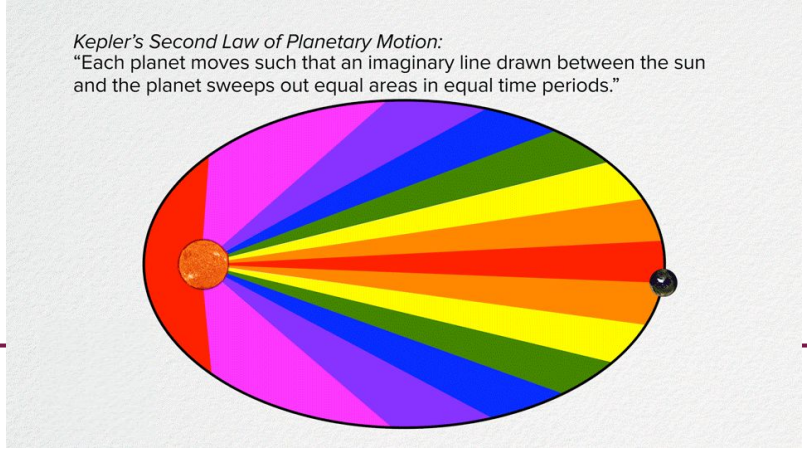




Kepler's Second Law

Kepler's Second Law states that the straight line joining a planet and the Sun sweeps out equal areas in space in equal intervals of time.

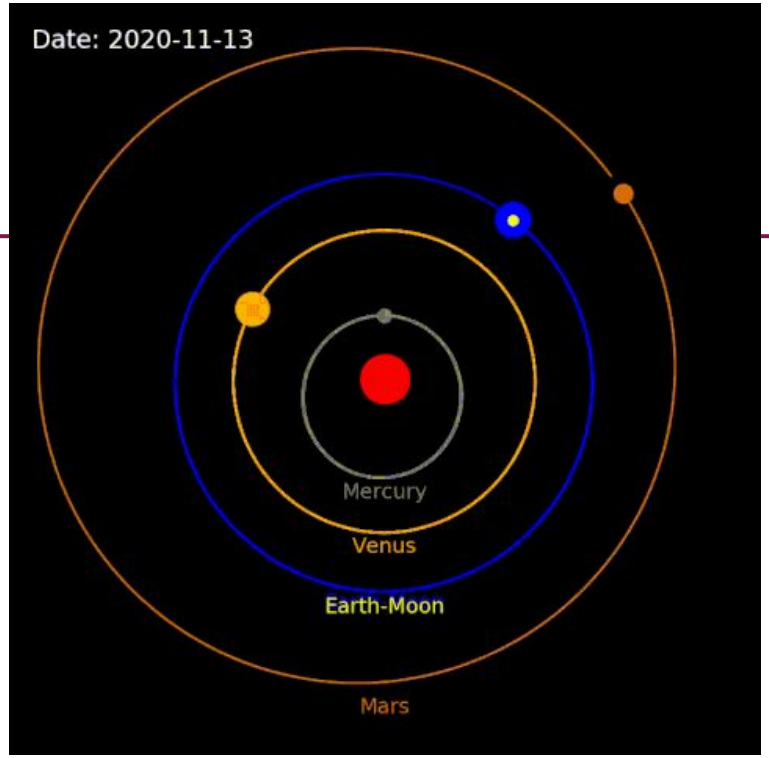




Kepler's Third Law

Kepler's Third Law is the most mathematical:
$\mathbf{P^2 = a^3}$

The square of a planet's orbital period is directly proportional to the cube of the semimajor axis of its orbit.



Planet	P(yr)	a(A.U.)	P^2	a^3
Mercury	0.241	0.387	0.058	0.058
Venus	0.615	0.723	0.378	0.378
Earth	1	1	1	1
Mars	1.881	1.524	3.537	3.537
Jupiter	11.862	5.203	140.7	140.8
Saturn	29.456	9.534	867.7	867.9

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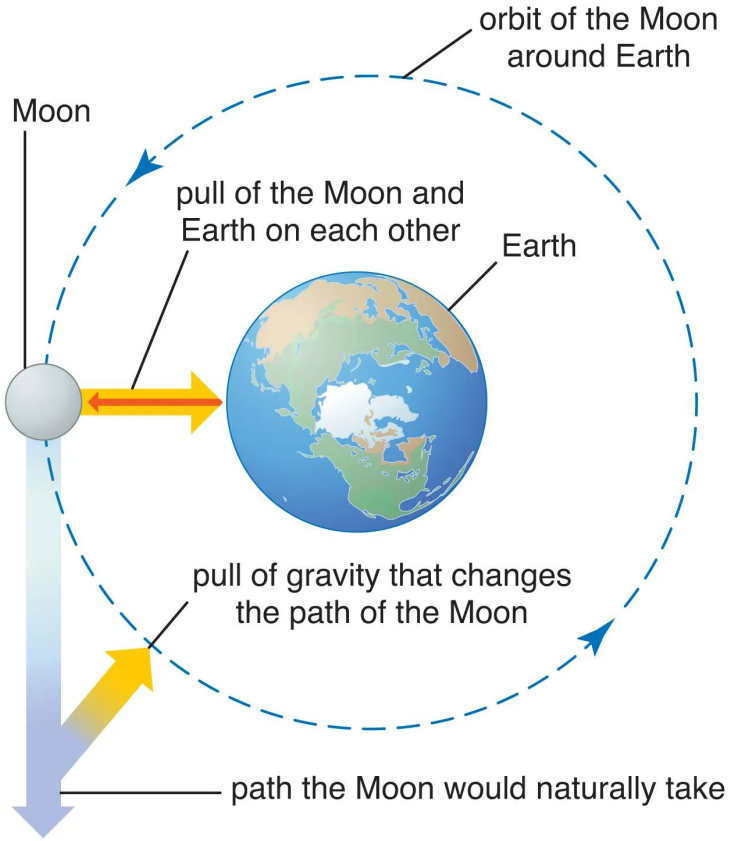
Kepler's Laws of Planetary Motion have stood up to all scientific evidence of the past 500 years.

Even though he didn't understand ***why*** (This is Newton's Law of Universal Gravitation) the planets acted this way, he showed that they did.



Galileo Galilei, Father of Modern Science

Galileo is responsible for the modern view of science and the transition from authority-based “science” to an observation-based science.

Galileo developed experiments to study:

- How objects would move without friction (the basis of the law of inertia)
- How objects accelerate (the basis of the law of gravity)

Galileo Galilei, Father of Modern Science

The telescope was invented in Holland around 1608, and Galileo improved the design in his workshop. His first few observations at amazed him:

1. **Craters, peaks on the moon**
2. Stars too faint to see by eye
3. Moons around Jupiter
4. Rings around Saturn
5. Spots on the Sun

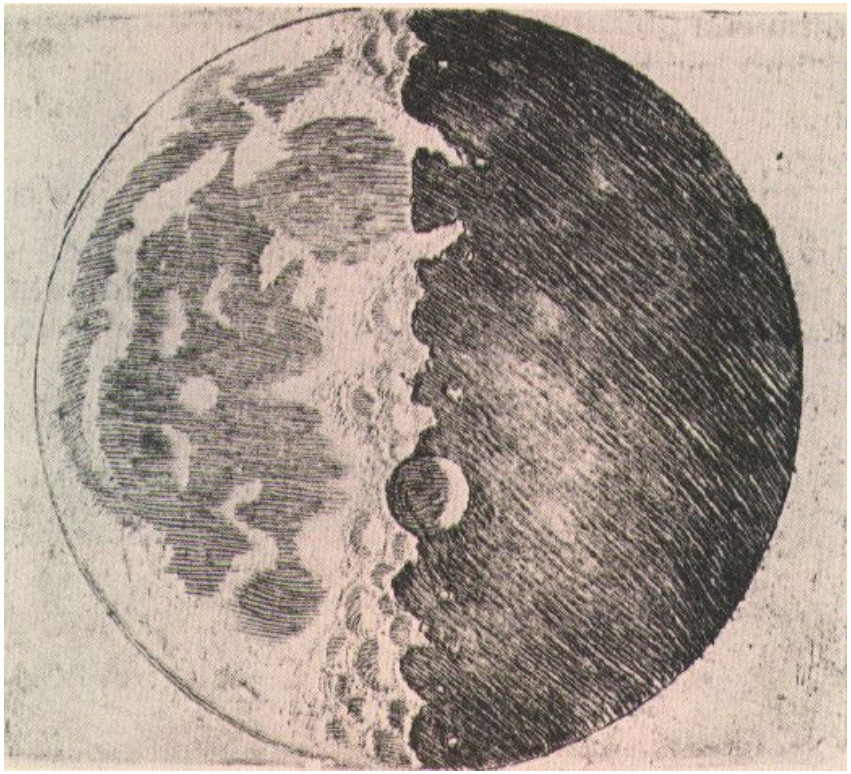
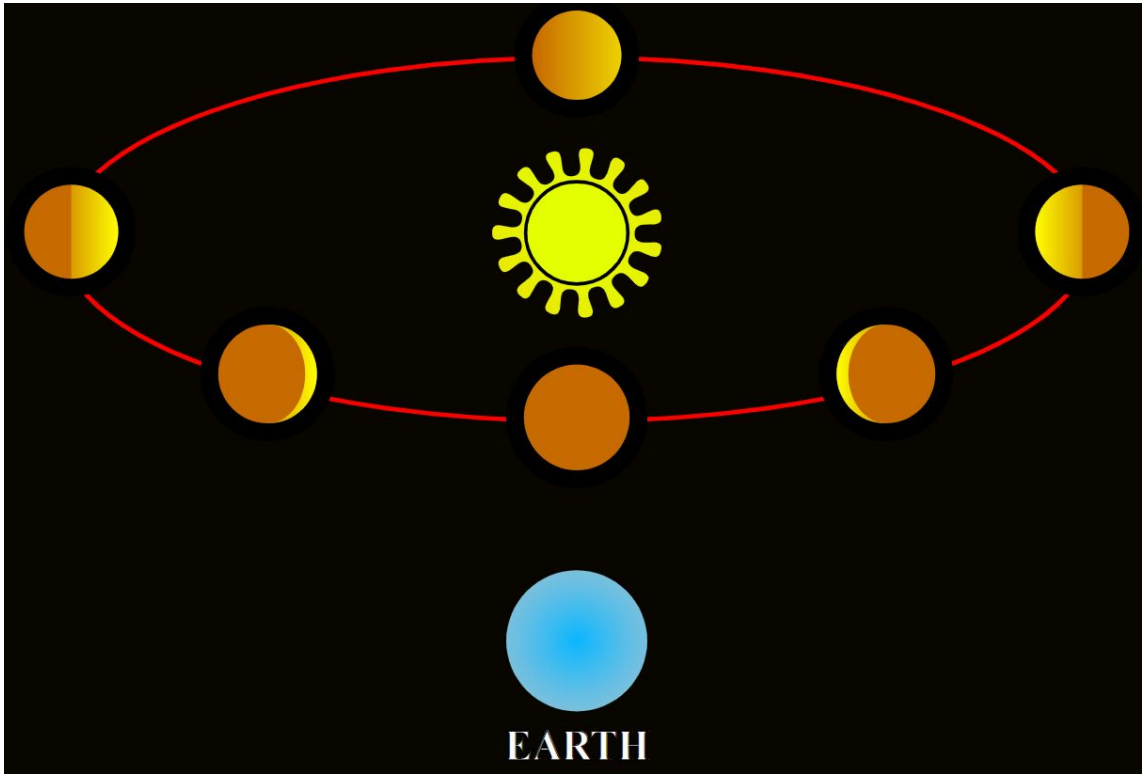


Image Credit Link: https://www2.hao.ucar.edu/Education/FamousSolarPhysicists/galileo-drawings-writings

Galileo Galilei, Father of Modern Science

Beyond this initial list, the definitive proof that the Earth **could not** be at the center of the solar system was Galileo's observation of the **phases of Venus**.

http://astro.unl.edu/classaction/animations/renaissance/venusphases.html



The observations of Venus's phases was the final nail in the coffin of all of the geocentric "universe" models.

By Nichalp, Public Domain, https://commons.wikimedia.org/w/index.php?curid=857453

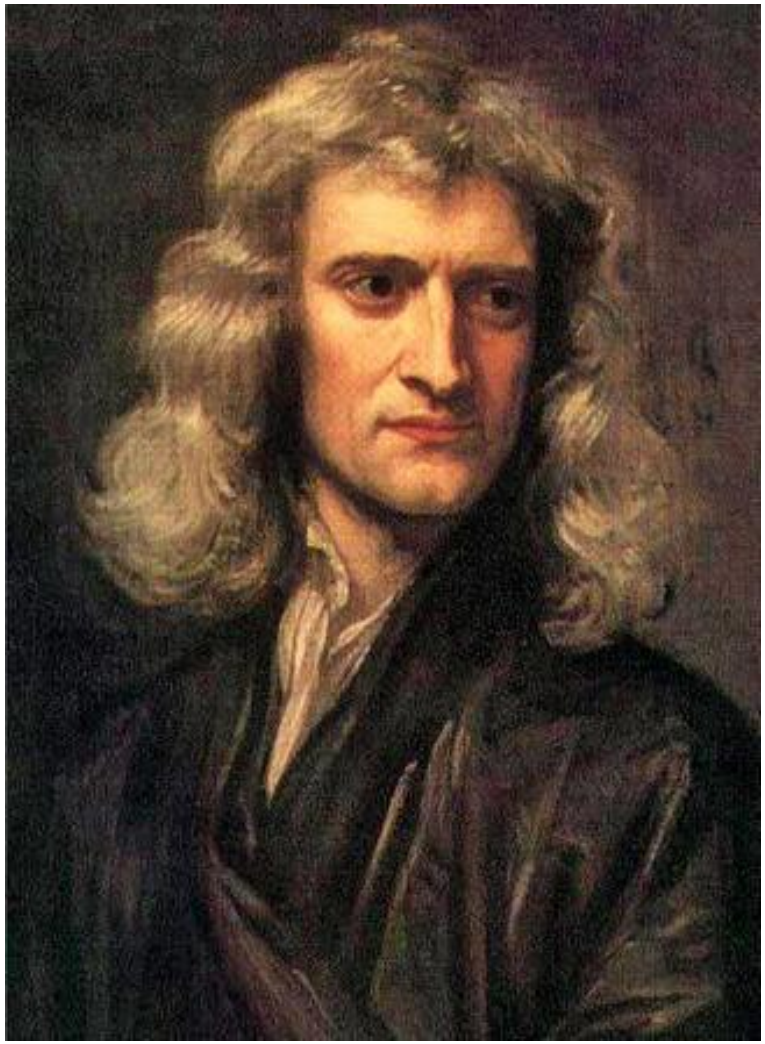
Galileo Galilei, Father of Modern Science

Within 40 years of the observations, only the heliocentric “universe” was taught. This was not without pushback from the Roman Catholic Church.

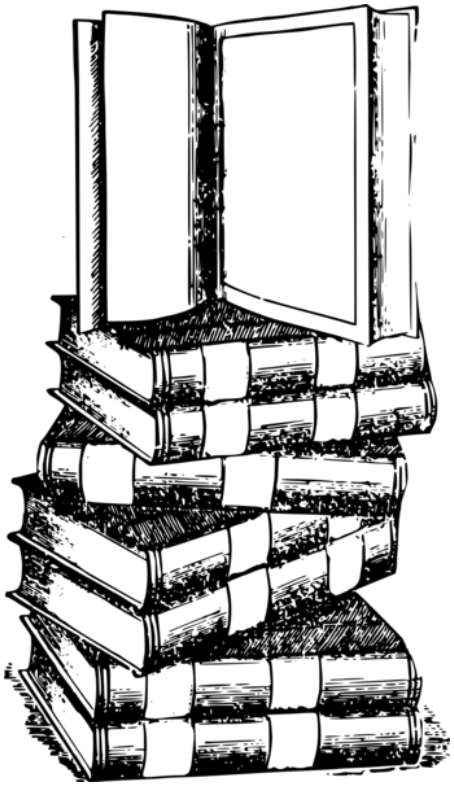
Galileo published *Dialog Concerning the Two Chief World Systems* with permission from local censor in Florence and the head censor at the Vatican in 1630. However, he was charged with disobeying the papal decree from 1616 (not heresy) and convicted in 1632.

He was sentenced to spend the rest of his life under house arrest. His work became a foundation of the Newtonian revolution in science.

His books were on the Church’s forbidden list until 1836. He was “found innocent” in 1992 by a special commission (i.e. they admitted they were wrong).



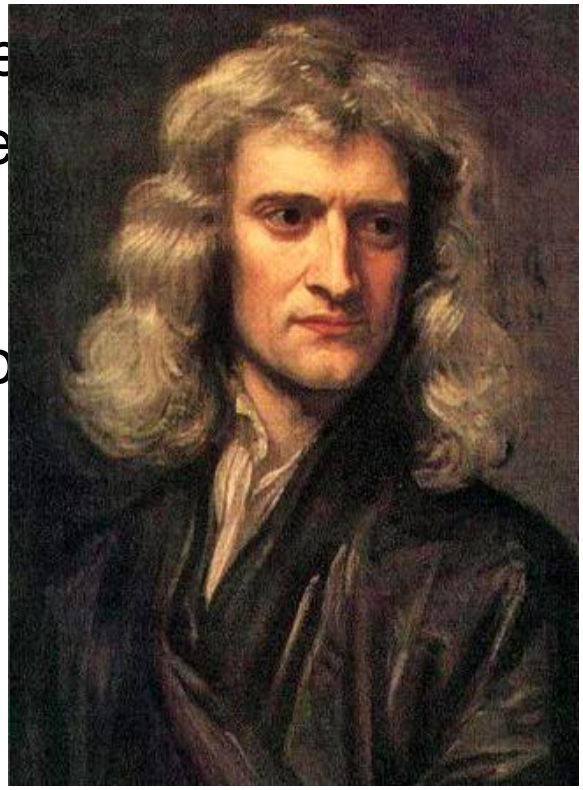
Chapter 3: Orbits and Gravity



Isaac Newton and Orbital Motion

By the time Isaac Newton was born, mode
been 100 years in development, laying the
we still use today.

Isaac Newton created new ***physical*** interp
mathematical descriptions of astronomy
Copernicus, Kepler, and Galileo.



Isaac Newton and Orbital Motion

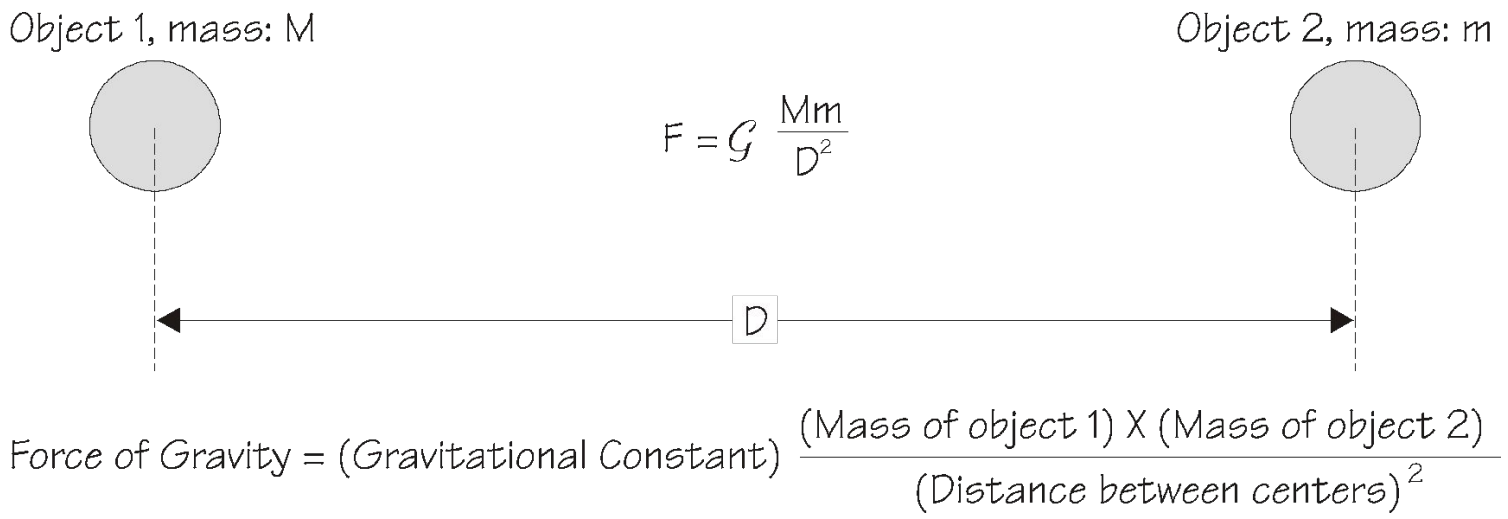
Newton developed the **universal law of gravitation**, a short equation (see right) which says that there is a force between any two masses.

$$F = G\frac{Mm}{r^2}$$

The **acceleration of gravity** of the Earth, Moon, or ot
body does not depend on the mass of the dropped ol
already determined that, and Apollo 15 showed it on t
hammer and a feather!

Isaac Newton and Orbital Motion

The only requirement for gravity to act on an object is that it has mass (i.e. it physically exists) and there is another object with mass anywhere in the universe.



Pause-and-Think MC Question:

Which of the following would cause the force on the Moon by Earth to increase by the largest amount?

1) double the mass of the Moon.
2) double the mass of Earth.
3) move the moon two times closer to Earth.
4) None of the above would change the force.

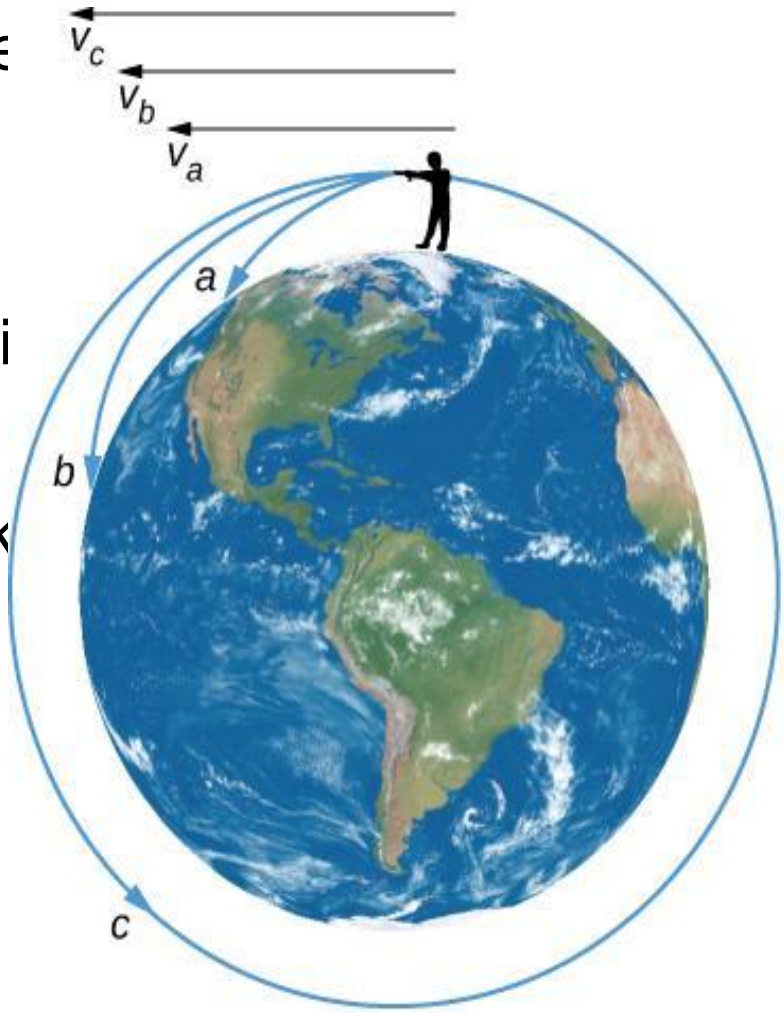
Newton's Law and Gravity

To be able to orbit something, we nee
enough.

Too slow: object falls back to Earth

Too fast: object escapes Earth's gravi

Just right: object is on a closed orbit.
for Earth is 17,500 miles per hour (8 k



Newton's Law and Gravity

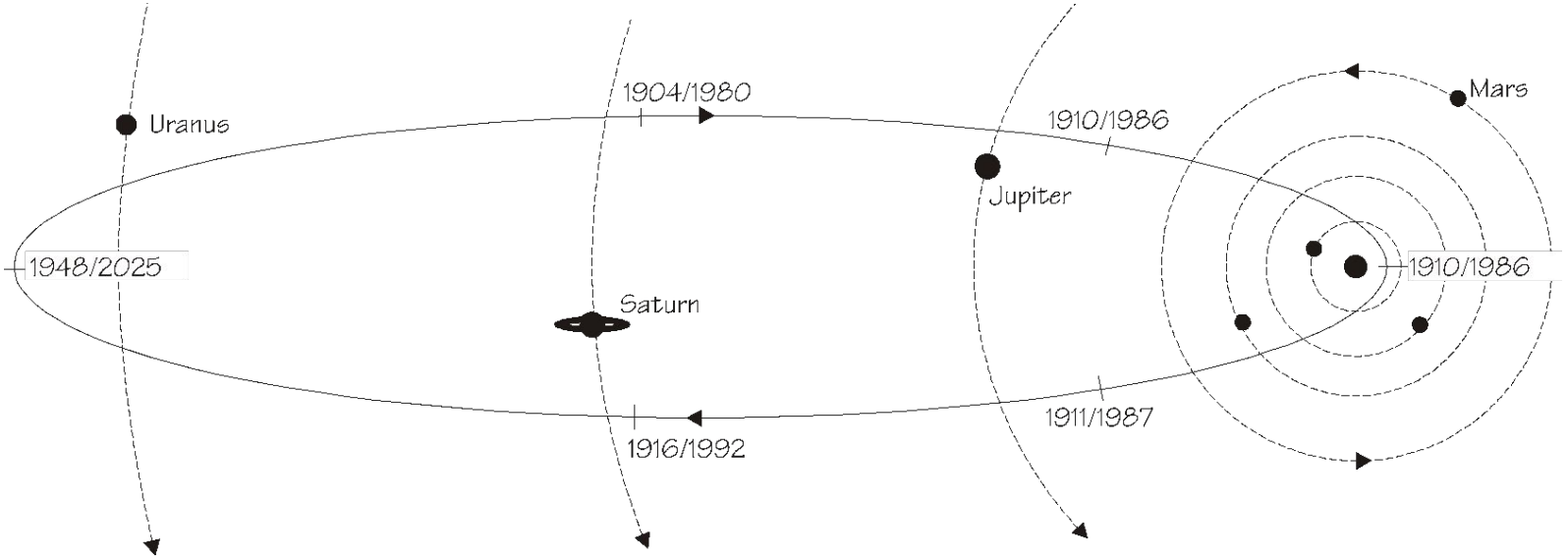
Newton's theories were published in 1688 ("Principia"). His Universal Law of Gravity combined with the Laws of Motion explain all three of Kepler's Laws of planetary motion.

These laws represent the "perfection" of the Copernican model. All planetary motions are explained with one equation, **gravity**. Geocentrism is finally wiped-out.

Can Newton's ideas be tested further?

Newton's Law and Gravity

Edmund Halley tracked part of the orbit of a comet, and predicted when it would return using Newton's laws of motion. He was exactly correct!



Newton's Law and Gravity

The planet Uranus discovered in 1781 by William Herschel. However, Uranus did not move according to predictions made with Newton's laws.

The inconsistencies could be explained by another massive object that was pulling on Uranus's orbit. Using Newton's laws of motion, a new planet was predicted to exist further from the Sun than Uranus. Neptune was found in 1845, less than 1° away from its predicted position!

Newton's laws are **testable and verifiable**. The discovery of Neptune is one the great stories of the scientific method. "If I have seen farther than other men, it is because I stood upon the shoulders of giants."