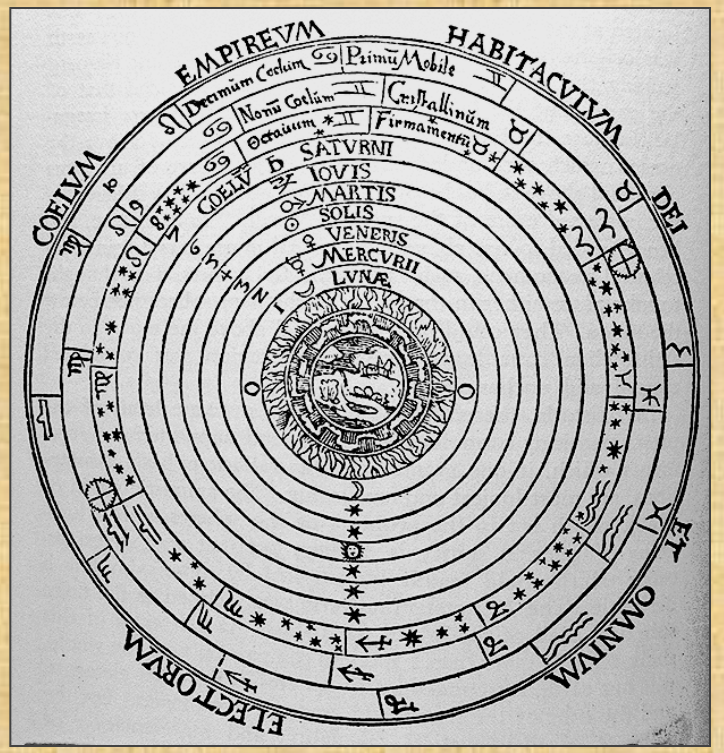
Lecture 5
The Copernican Revolution




NICOLAI COPERNICI

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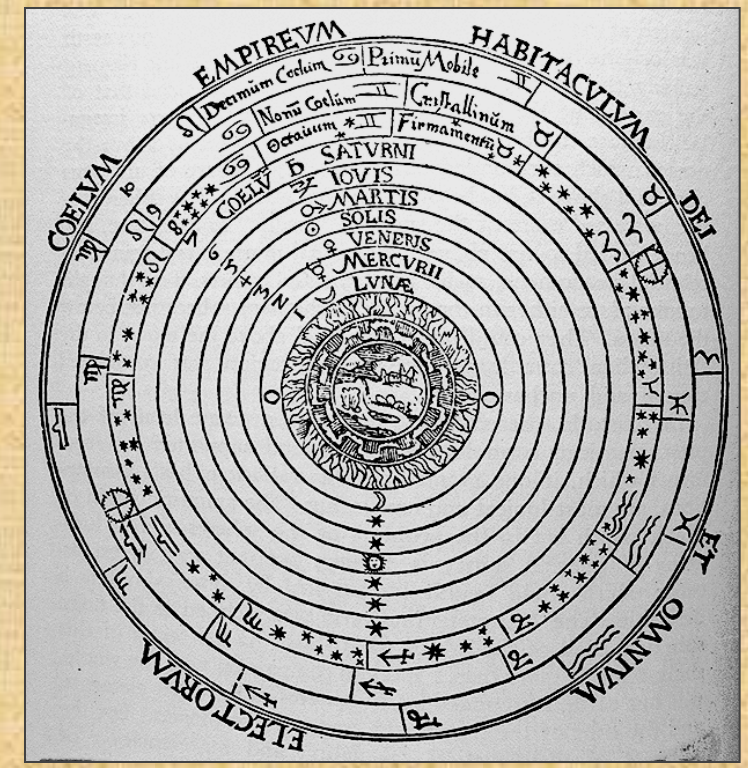
pulcherimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum simul possit illuminare. Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentẽ omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoq; minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximã Luna cũ terra cognationẽ habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

The Universe of Antiquity

Prior to the year 1600 man's naked-eye observations of the heavens had revealed:

- Ancient people
  - Invented **constellations**
  - Developed **monthly & yearly calendars**
  - Tracked **planets' motions**, etc.
  - Predicted **eclipses**

- **Greeks (Ptolemy)** developed concept of **celestial sphere in an Earth-centered universe**
  - Earth "obviously" a motionless sphere
  - Seven wanderers (planets, moon, Sun) went around the Earth in "perfect" circles
  - Stars circled Earth beyond planets



This simplistic, unquestioned view of the universe, based on naked-eye observations, held for over 1500 years. But some wondered if this view might be wrong…

Challenging the Earth-centered model

- Copernicus proposed a **Sun-centered** (*heliocentric*) model in 1543.
- Used *moving Earth* in solar system!
- Revolutionary paradigm took time to become accepted.
- No more accurate than the Ptolemaic model in predicting planetary positions because it still used perfect circles.

Copernicus (1473-1543)

Copernicus' Universe

- Earth is rotating planet in circular orbit around Sun
- **Heliocentric** model explained:
  - daily changes
  - yearly changes
  - Retrograde motion of planets
- Revolutionized humanity's view of its place in "Universe"
  - Earth is a planet that moves in circular orbit just like all other planets
  - Challenged primacy of Earth in Universe - Earth no longer center

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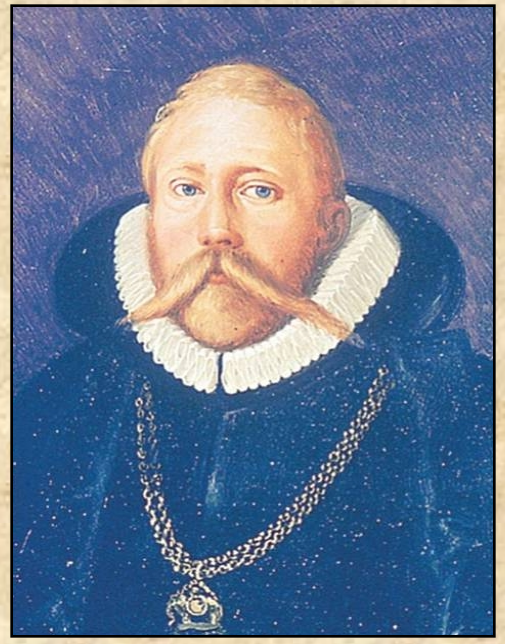
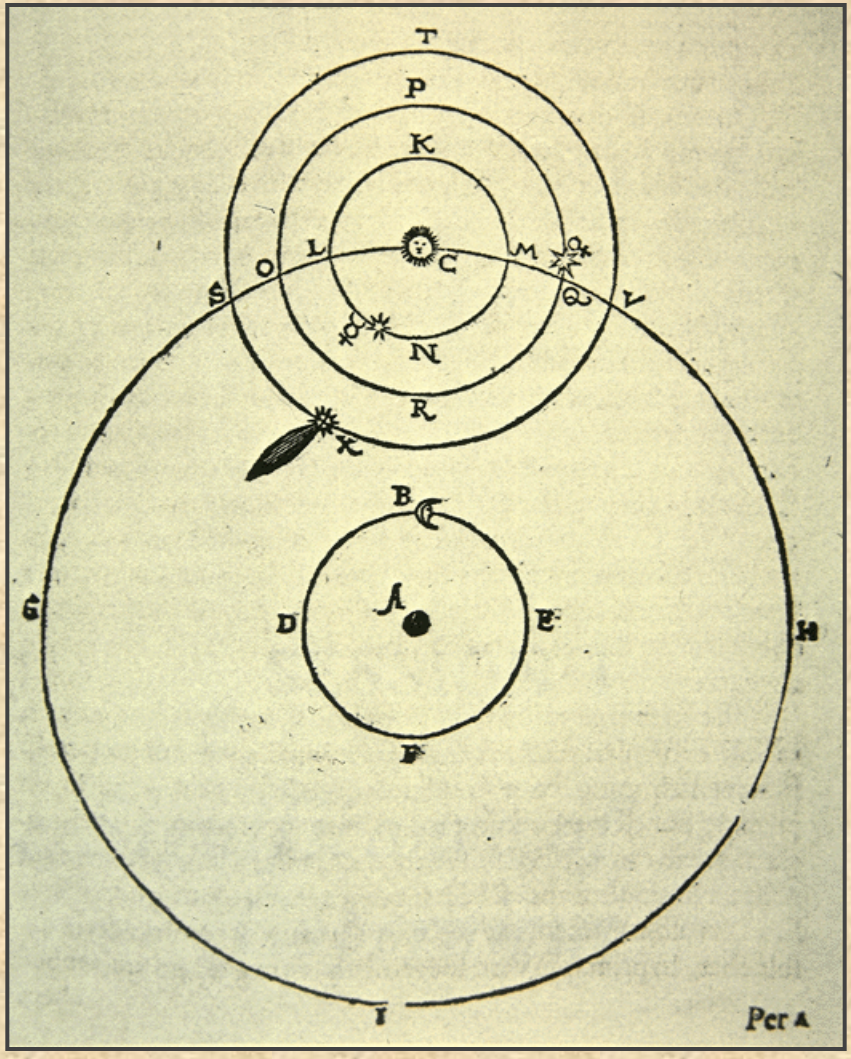
Tycho Brahe (1546-1601)

- Made extensive, systematic, *accurate* naked-eye observations
  - 777 stars observed to high accuracy
  - Sun, moon, planets (esp. Mars) for 20 yr throughout orbits
  - Found existing predictions off by a month!
- Invented new, better instruments
- Established first "observatory"



Brahe's "Universe"

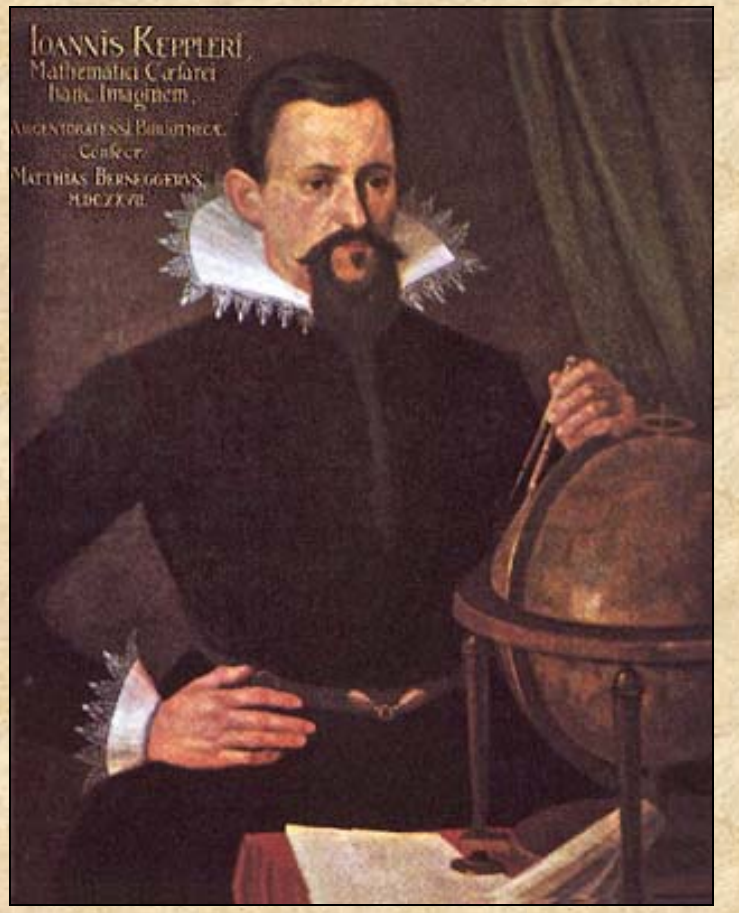
- Rejected Ptolemaic model
  - inaccurate predictions
- Couldn't accept Copernican model
  - What *moved* massive Earth?
  - Stars would dwarf our Sun
  - Couldn't detect stellar motions
- Compromised
  - Moon & Sun orbited Earth
  - *Planets orbited Sun*
- Finally hired Kepler, who used Brahe's observations to discover the truth about planetary motion.



Johannes Kepler (1571 - 1630)

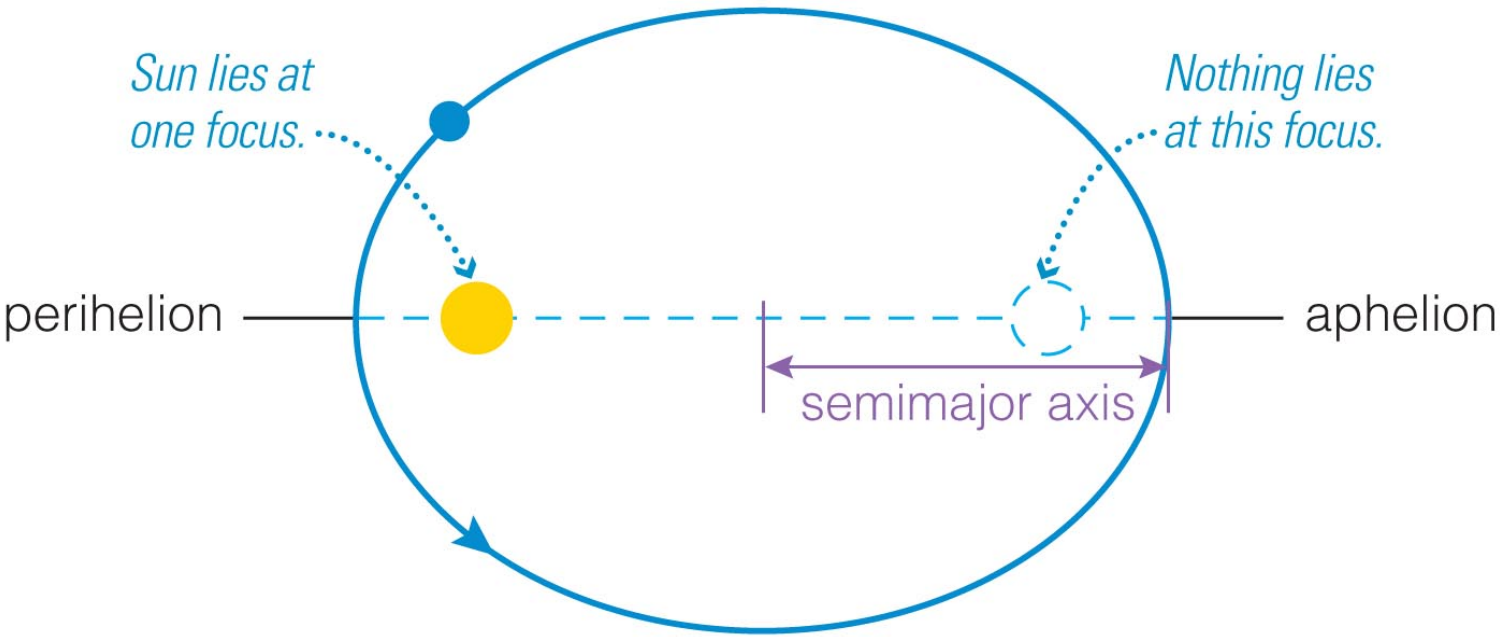
- Used Brahe's observations.
  - Could not fit Brahe's data to circular orbits (especially Mars – 8' error)
  - *Trusted data not beliefs*
  - Observations could only be explained with **ellipses**!

- Developed 3 "laws" of planetary motion and became the founder of celestial mechanics.



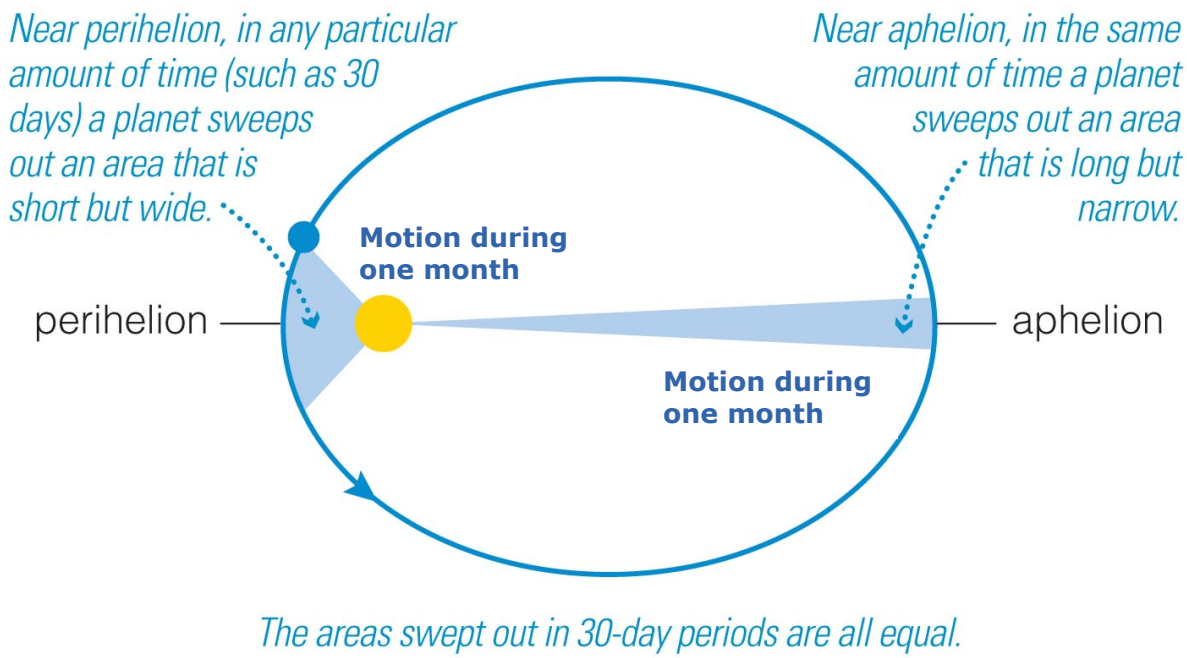
Kepler's First Law

- The orbit of each planet around the Sun is an ***ellipse*** with the Sun at one focus.
- **Perihelion** – closest approach
- **Aphelion** – farthest distance



Kepler's Second Law

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



This means that *a planet travels faster when it is nearer to the Sun and slower when it is farther from the Sun.*

Kepler's Third Law

More distant planets orbit the Sun at slower average speeds, obeying the relationship

$$p^2 = a^3$$

p = orbital period in years
a = length of semimajor axis from Sun in AU

Example: **Mars**

p = 1.88 years	a = 1.52 AU
p^2 = 1.88 x 1.88	a^3 = 1.52 x1.52 x 1.52
= 3.53	= 3.51

Think/Pair/Share

An asteroid orbits the Sun at an average distance $a = 4$ AU. How long does it take to orbit the Sun?

A. 4 years
B. 8 years
C. 16 years
D. 64 years

Hint: Remember that $p^2 = a^3$

Think/Pair/Share

An asteroid orbits the Sun at an average distance $a = 4$ AU. How long does it take to orbit the Sun?

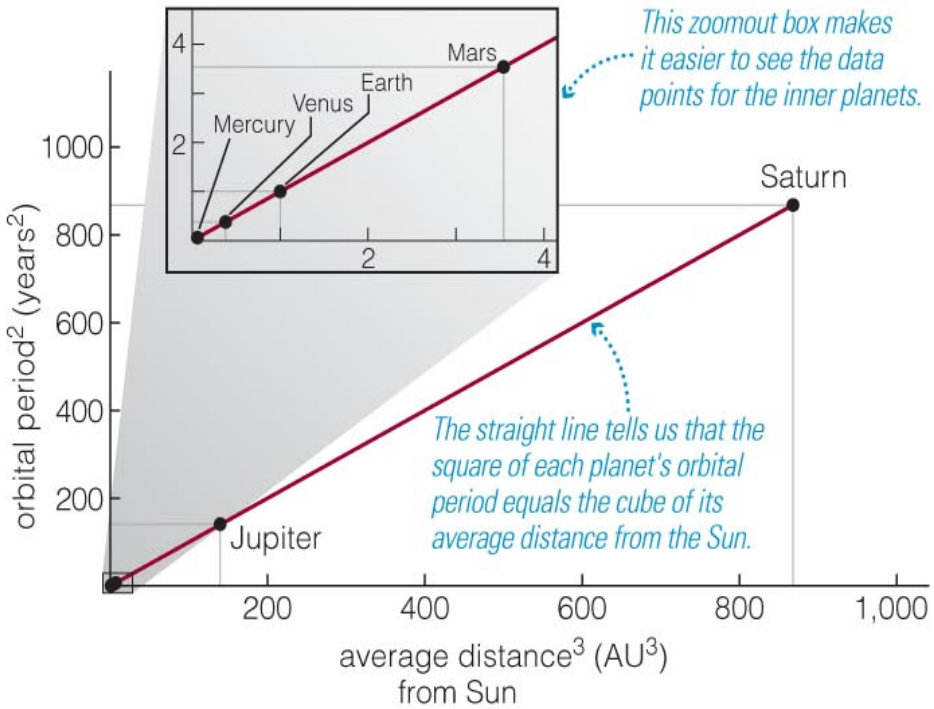
A. 4 years
B. 8 years
C. 16 years
D. 64 years

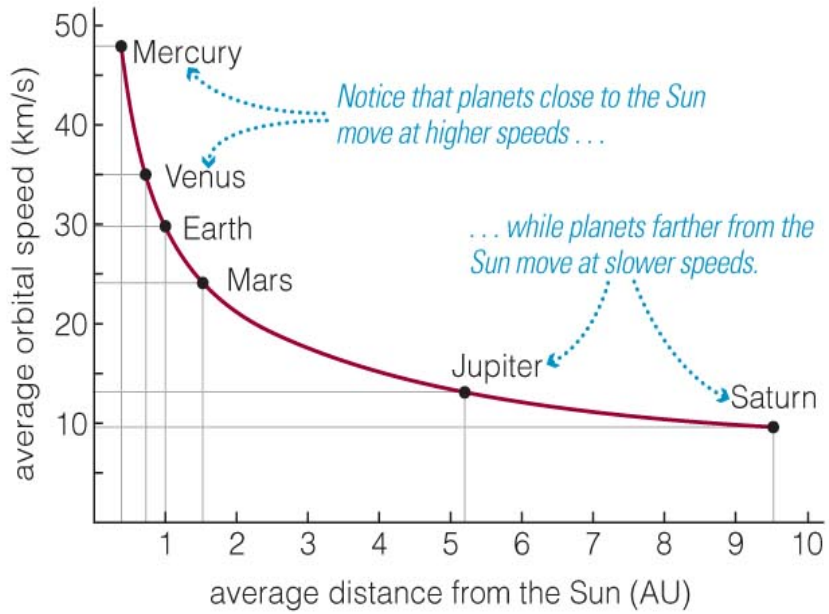
We need to find p so that $p^2 = a^3$.

Since $a = 4$, $a^3 = 4^3 = 64$.

Therefore, $p = 8$, $p^2 = 8^2 = 64$.

Graphical version of Kepler's Third Law





Kepler's 3rd law is a powerful tool in exploring the motions of many objects in universe – planets, stars, galaxies, etc

What have we learned?

Begin 3 minute review

What have we learned?

How did Copernicus challenge the Earth-centered universe?

Copernicus proposed a **heliocentric** model; Brahe provided the **data** needed to improve this model; Kepler found a **model** that fit Brahe's data.

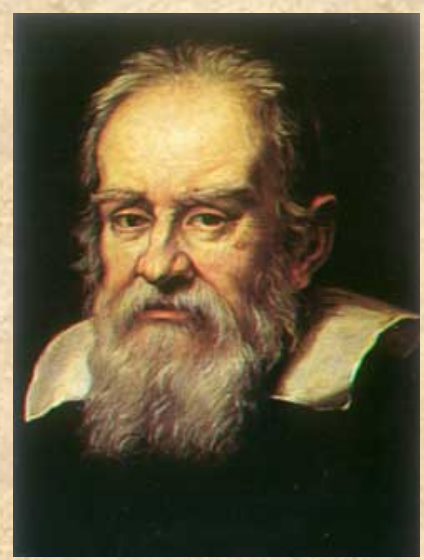
What are Kepler's three laws of planetary motion?

1. The orbit of each planet is an **ellipse** with Sun at one focus.

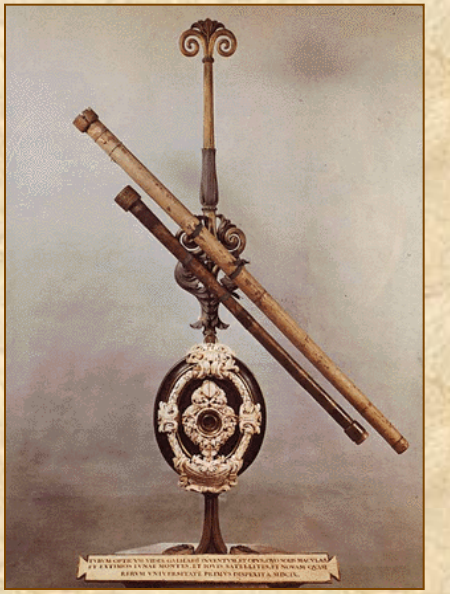
2. As a planet moves around its orbit it sweeps out **equal areas in equal times**.

3. More distant planets orbit the Sun at slower average speeds: $p^2 = a^3$.

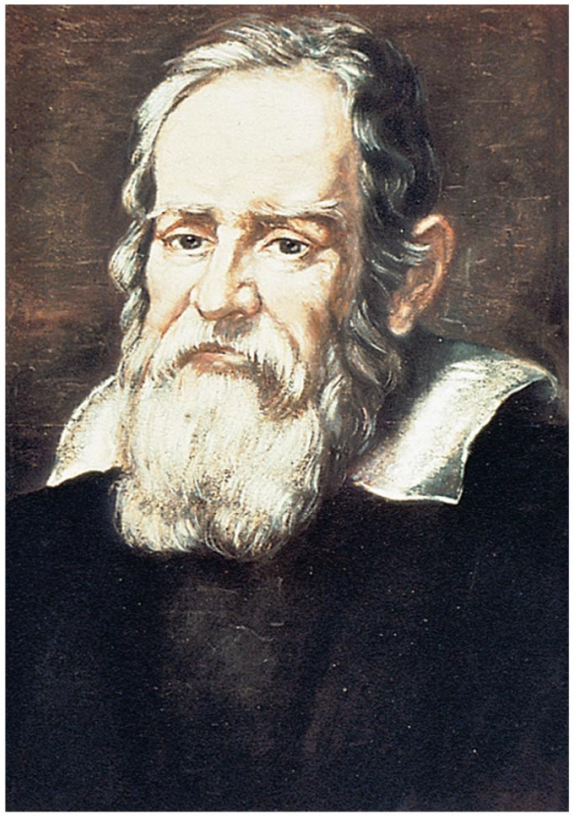
Galileo Galilei



- *Simplistic view of the heavens changed dramatically with* ***telescope****.*
- Galileo first observed heavens with a telescope in 1609 but many were close-minded, refused to believe; Church forced Galileo to recant.
- But undeniable proof was there for all to see. *His observations proved Copernicus' heliocentric model true.*



How did Galileo prove the Copernican revolution?



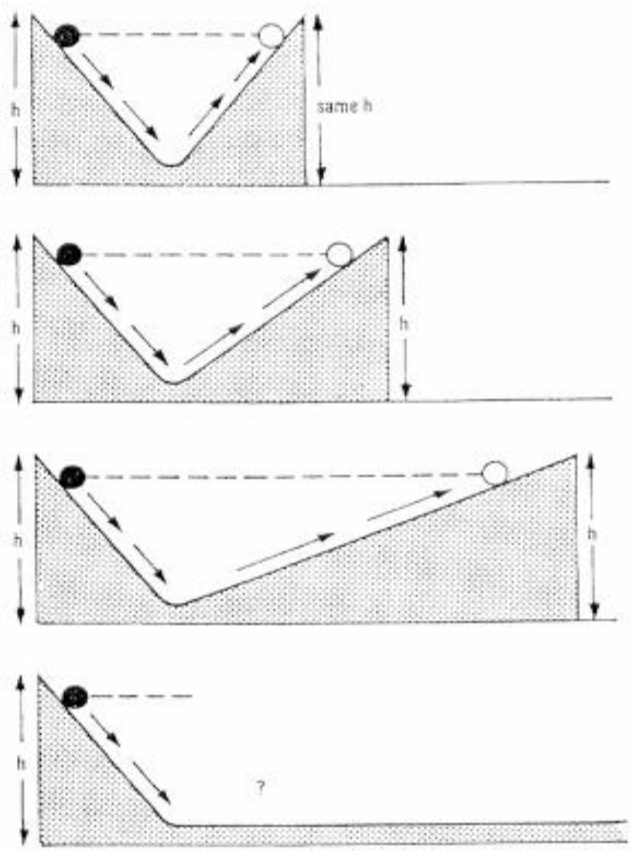
Galileo (1564–1642)

Galileo overcame major objections to the Copernican view. Three key objections rooted in the geocentric view were:

1. Earth could not be moving because objects in air would be left behind.
2. Non-circular orbits are not "perfect" as heavens should be.
3. If Earth were really orbiting Sun, we'd detect stellar parallax.

How did Galileo prove the Copernican revolution?

Overcoming the first objection (nature of motion):

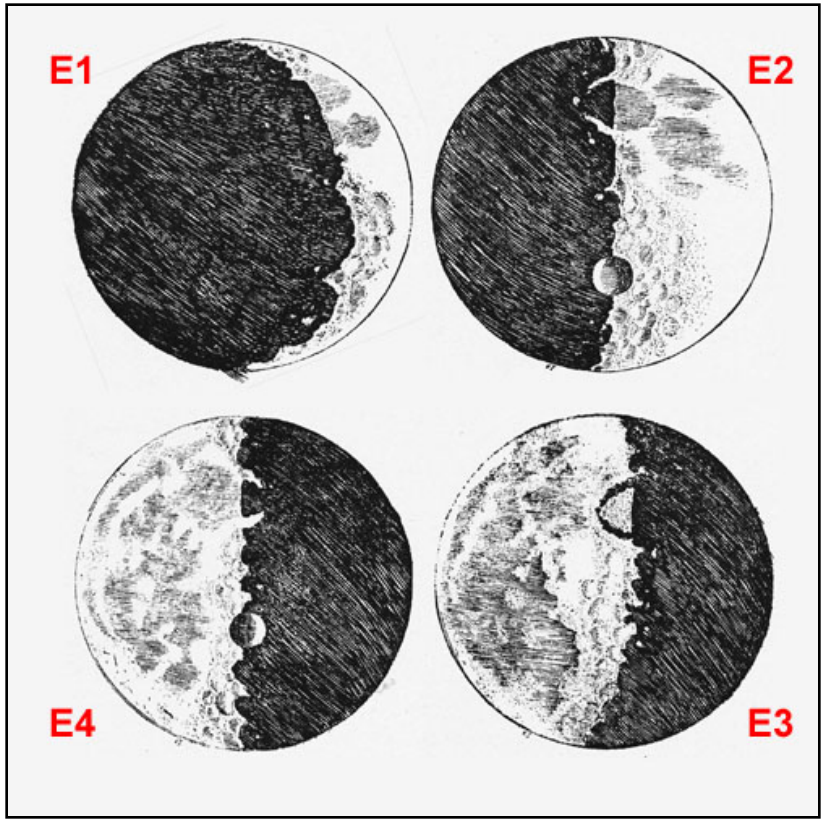


Galileo's experiments showed that objects in air *would* stay with Earth as it moves.

- Aristotle thought objects "naturally" come to rest.
- Galileo showed that *objects will stay in motion* unless something slows them down (friction).

How did Galileo prove the Copernican revolution?

Overcoming the second objection (heavenly perfection):

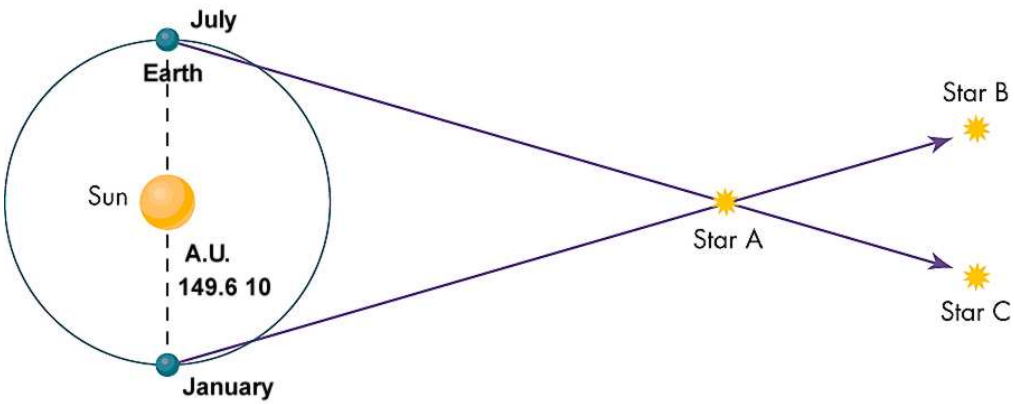


Using his telescope, Galileo saw:

- Mountains, valleys, craters on Moon
  - Contradicted view that any heavenly body was "perfectly" smooth
- Sunspots on Sun ("imperfections")

How did Galileo prove the Copernican revolution?

Overcoming the third objection (parallax):

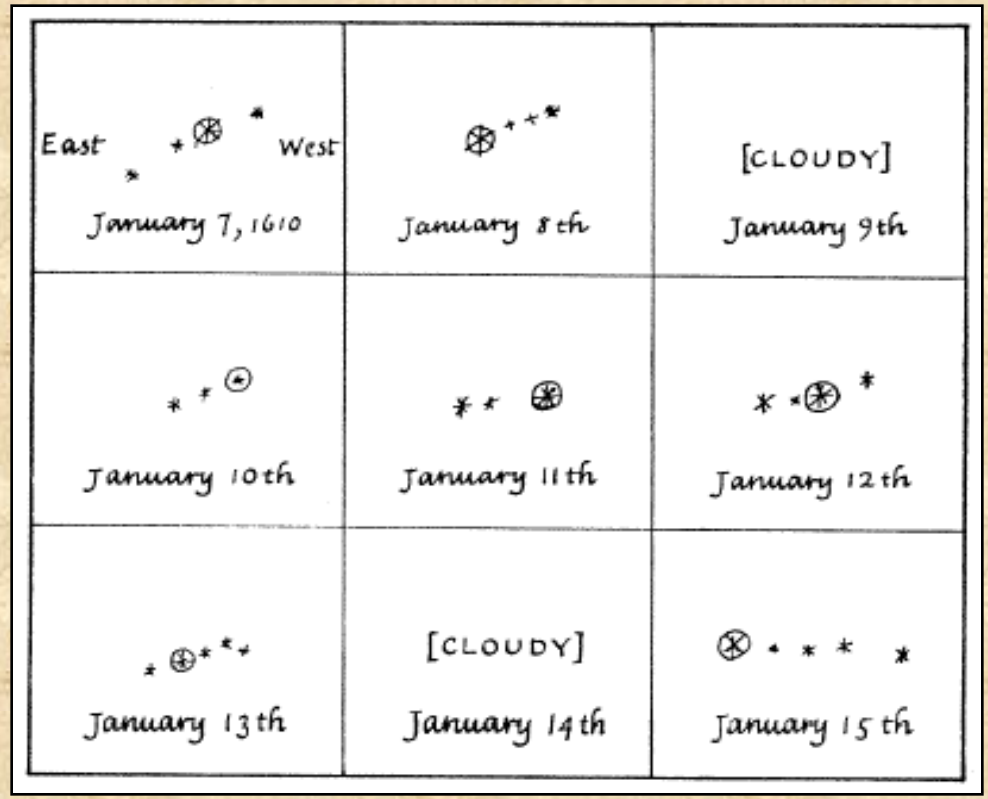


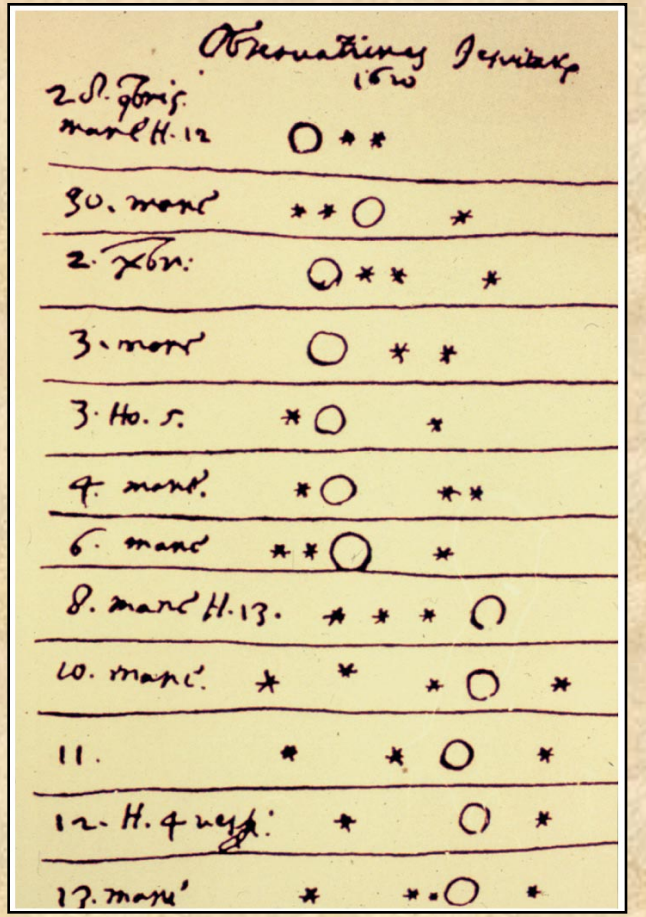
• Galileo showed stars must be extremely far away — his telescope showed the Milky Way as countless individual stars.

• If stars were much farther away, then lack of detectable parallax was no longer so troubling.

Jupiter observations

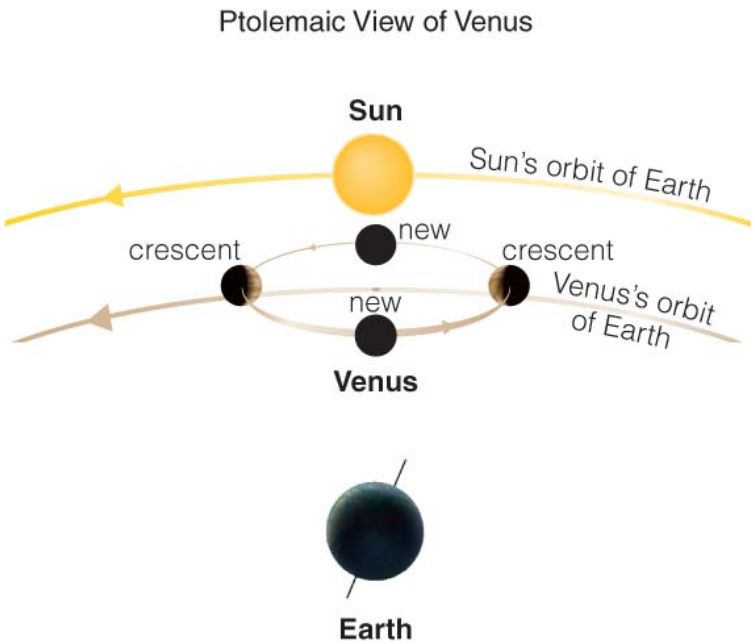
- Planet orbited by four moons!
  - Jupiter center of motion, not Earth
  - *Visible contradiction of Ptolemaic model*

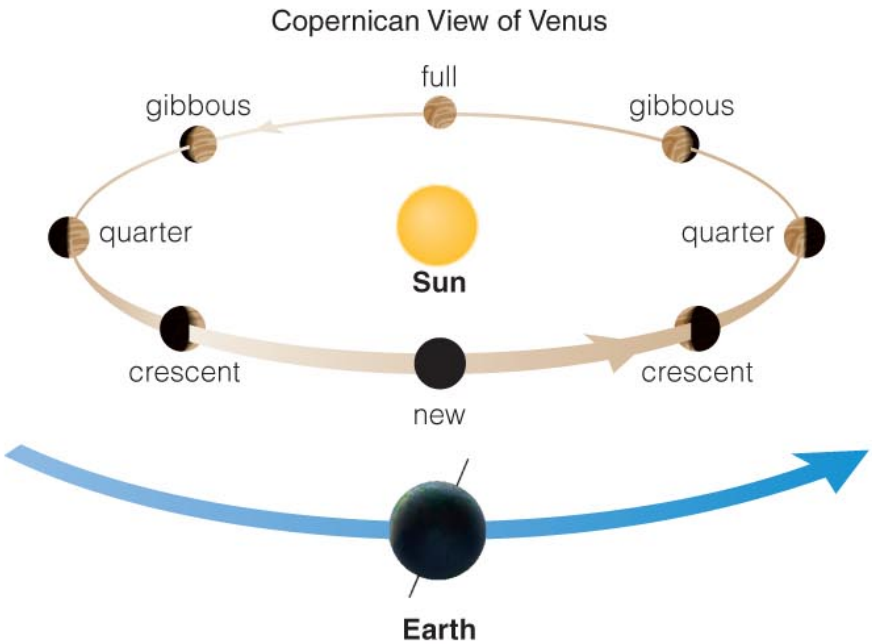




Galileo saw four moons orbiting Jupiter, proving that not all objects orbit Earth.

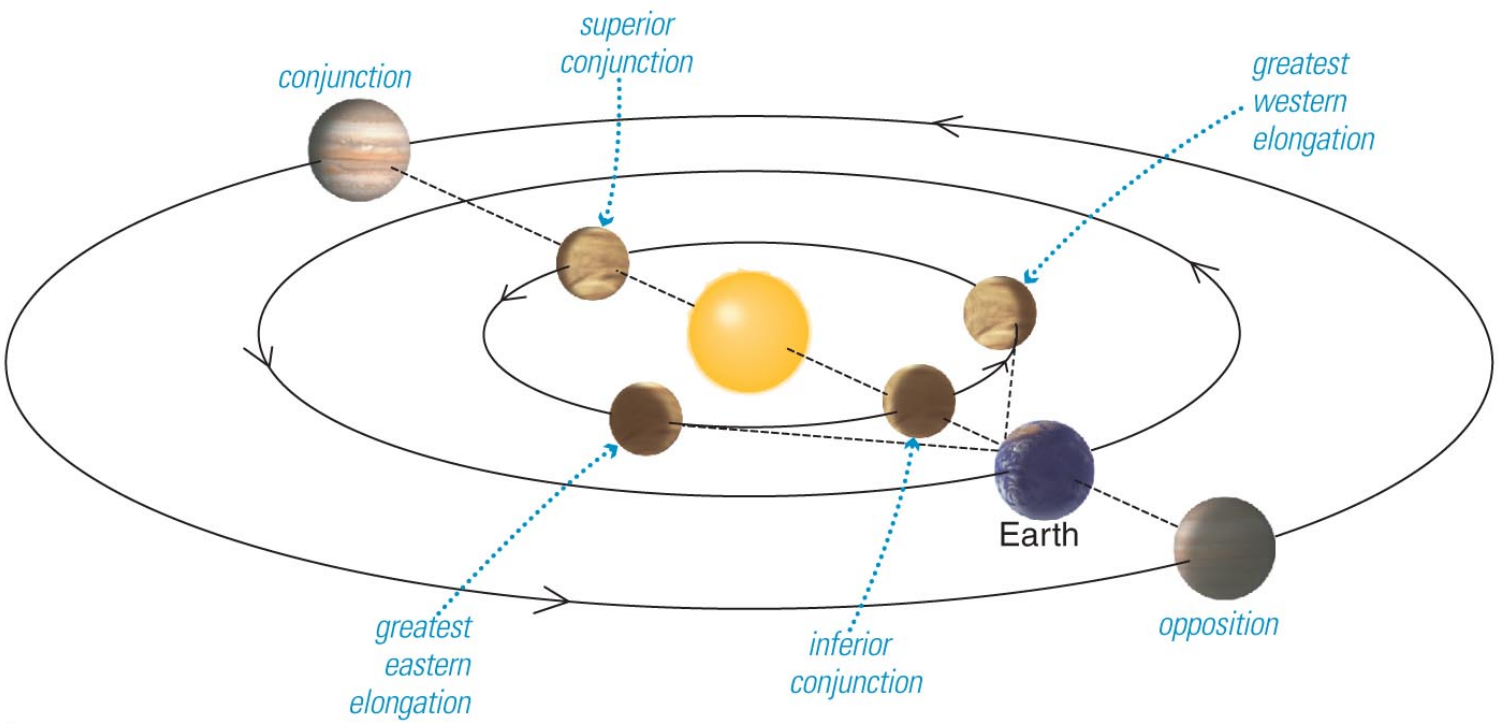
Galileo's observations of Venus





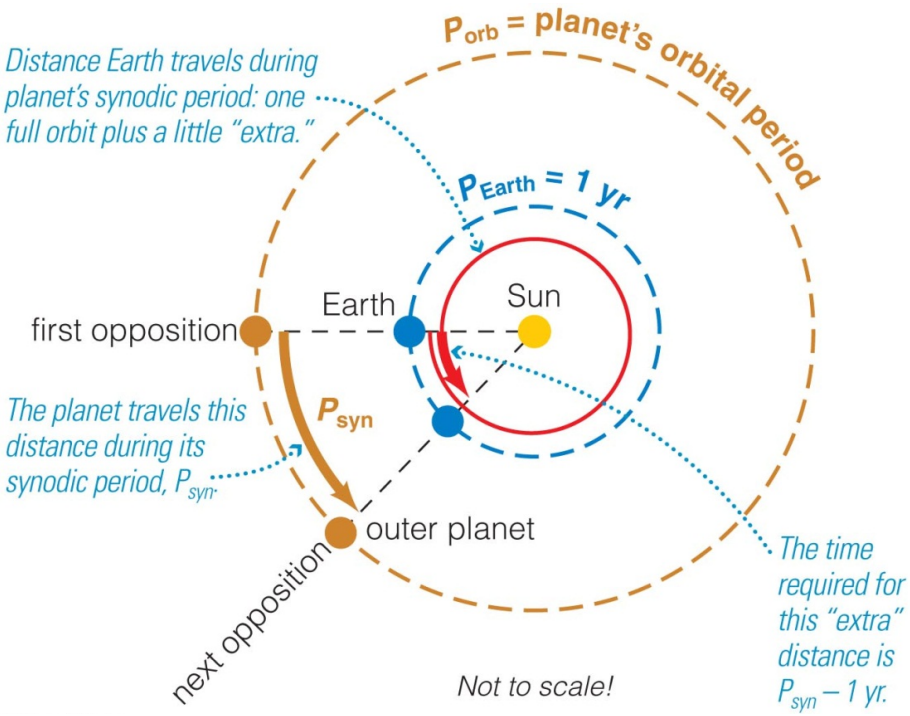
- Galileo's observations of phases of Venus proved that it orbits the Sun and not Earth.
- *A full Venus can't be seen in Ptolemaic universe.*

How did the heliocentric universe explain planetary orbits?



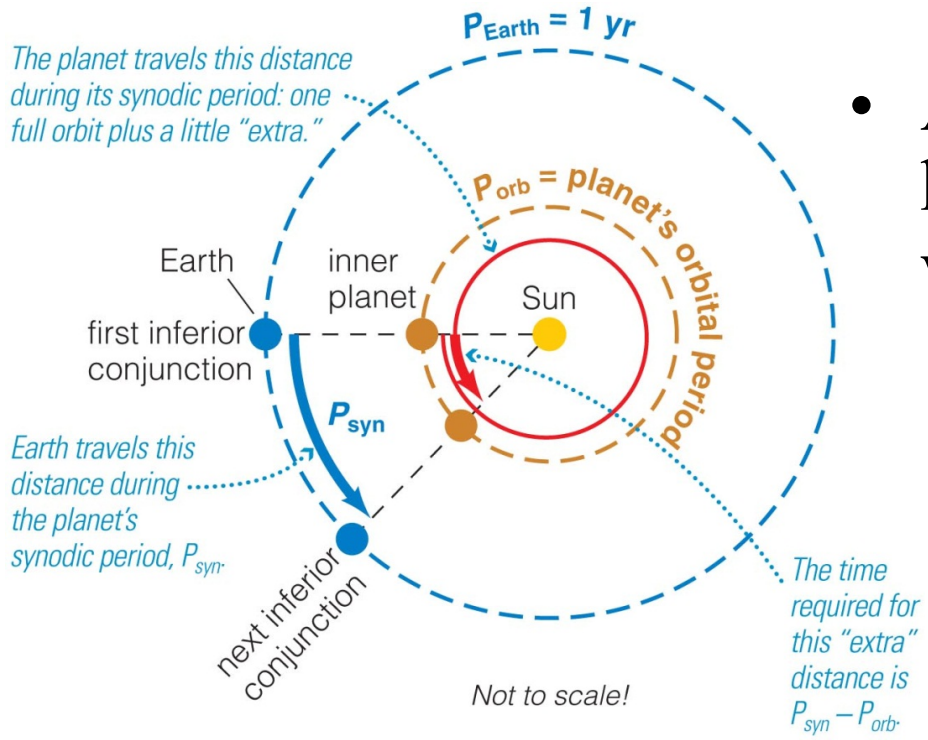
- Planets were now understood to move relative to Earth
- Planets could appear at **opposition, elongation,** and **conjunction**

Sidereal period



- A planet's **sidereal** period is simply how long it takes to orbit the Sun.

Synodic period



- A planet's **synodic** period is how long it takes to line up with Earth and Sun
  - **Inner planets:** planet's sidereal period plus distance *Earth* moves in that time
  - **Outer planets**: one year plus distance *planet* travels in one year

What have we learned?

Begin 3 minute review

What have we learned?

What was Galileo's role in proving the Copernican heliocentric solar system?

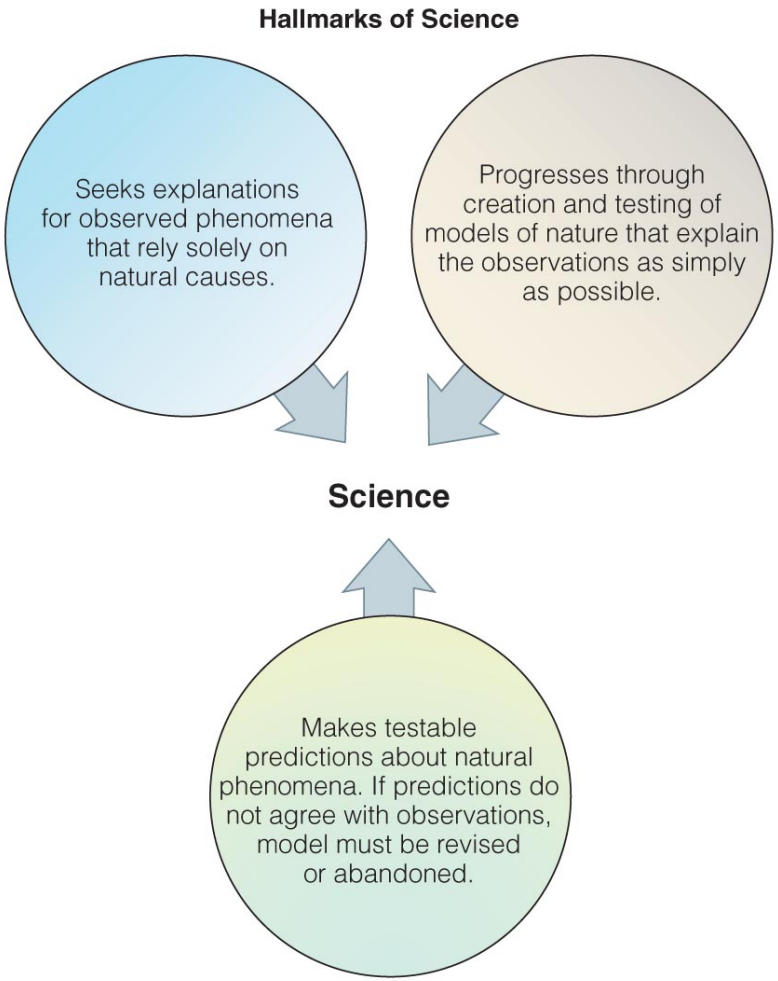
1) His observations provided **evidence** to support the Sun-centered, heliocentric solar system of Copernicus.

2) His experiments overcame the remaining objections to the Sun-centered solar system model.

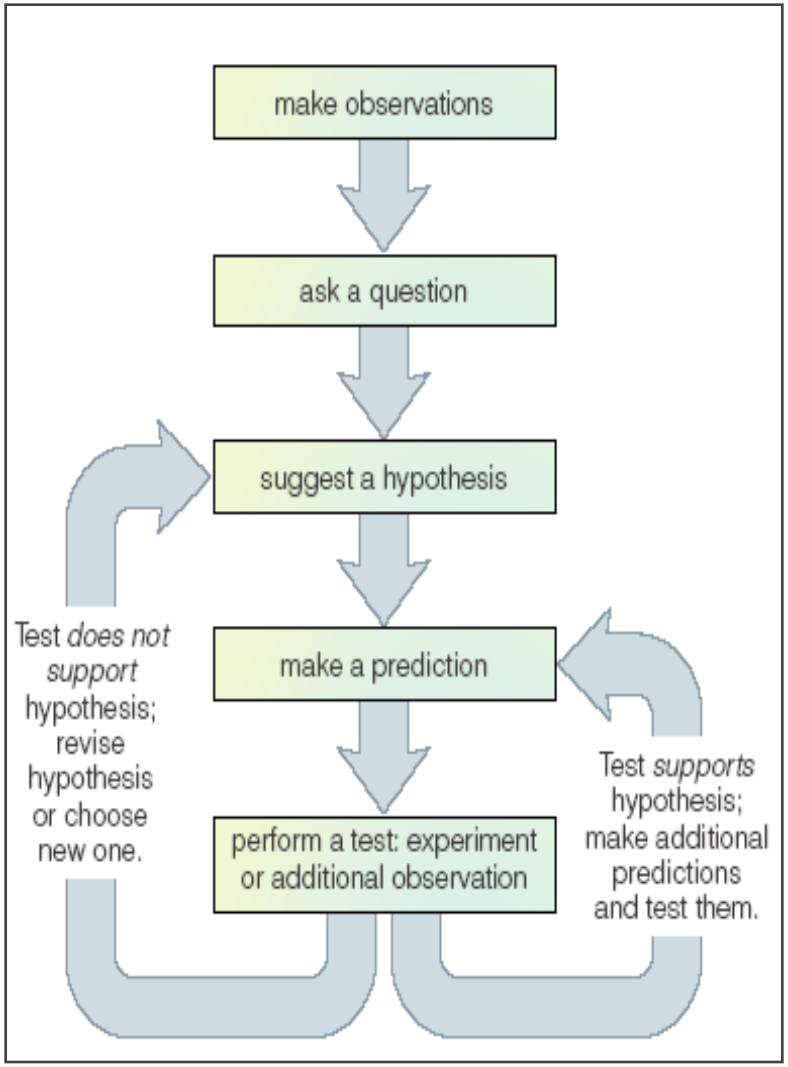
How do we learn about the universe?

1. Science seeks **natural explanations** for observed phenomena. (A scientific model cannot include divine intervention).
2. Science progresses through the creation and testing of **models** that *explain the observations* as simply as possible.
3. A scientific model must make **testable predictions** that would force us to revise or reject the model if the predictions are proven wrong.

Let's look at *how* science is done…



The Scientific Method



While not *all* knowledge comes from science, it is our best tool for understanding the natural world.

- **Science**: our key to understanding
  - Based on what we observe (not imagine)
  - Propose a *hypothesis* – what natural explanation (model) might explain what we see?
  - Testable prediction – verify model repeatedly
  - Unconfirmed model may be revised or discarded
  - Confirmed model = *theory*

What is a scientific theory?

- Many think a "theory" is just an untested idea or guess.
- In science, a theory is NOT the same as a hypothesis, rather:
- A scientific ***theory*** must:
  - Explain a wide variety of observations with a few simple principles
  - Be supported by a large, compelling body of evidence.
  - NOT have failed any crucial test of its validity.
- A **fact** is a single piece of proven information – these are used to build a theory
- A scientific **law** describes natural relationships (Kepler's laws, law of gravity, etc.)

Accepted scientific theories are tested explanations of nature

Think/Pair/Share

Einstein's theory of relativity meets all the criteria of a scientific theory. This means:

A. Scientific opinion is about evenly split as to whether relativity is true.

B. Scientific opinion is about 90% in favor of the theory of relativity and about 10% opposed.

C. After more than 100 years of testing, Einstein's theory has successfully met every test of its validity.

D. There is no longer any doubt that the theory of relativity is absolutely true.

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What have we learned?

Begin 3 minute review

What have we learned?

What is the nature of science?

Science: seeks explanations that rely solely on **natural causes**; progresses through the creation and testing of **models** of nature; models must make testable predictions.

What is a scientific theory?

A model that explains a wide variety of observations in terms of a few general principles and that has survived repeated and varied **testing.**