The Ancient Mystery of the Planets

goals for learning:

• What was once so mysterious about planetary motion in our sky?

• Why did the ancient Greeks reject the real explanation for planetary motion?
Planets Known in Ancient Times

• Mercury
  – difficult to see; always close to Sun in sky

• Venus
  – very bright when visible; morning or evening “star”

• Mars
  – noticeably red

• Jupiter
  – very bright

• Saturn
  – moderately bright
What was once so mysterious about planetary motion in our sky?

- Planets usually move slightly *eastward* from night to night relative to the stars.
- But sometimes they go *westward* relative to the stars for a few weeks: apparent retrograde motion
Mars in The Sky

- This is a view of Mars from the Earth. We would see it against some of the background stars.
Where is Mars the Next Year?

- A year later, Earth is in the same place, but Mars is partway around its orbit so it appears against different background stars.
We see apparent retrograde motion when we pass by a planet in its orbit.
Explaining Apparent Retrograde Motion

• Easy *for us* to explain: occurs when we “lap” another planet (or when Mercury or Venus laps us)

• But very difficult to explain if you think that Earth is the center of the universe!

• *In fact, ancients considered but rejected the correct explanation*
Last night I saw Mars move westward through the sky due to its apparent retrograde motion.

A. Yes, this occurs during certain times of the year when Earth overtakes Mars in its orbit.

B. Yes, this is a well studied phenomenon and its explanation proved a challenge to ancient astronomers.

C. All planets (and stars) move westward because of Earth’s rotation, so this is not unusual.

D. No, apparent retrograde motion is only noticeable over many nights, not a single night.
How did the Greeks explain planetary motion?

1) Heliocentric model:

- Third century B.C. Aristarchus proposed the Sun as the center of planetary motion.

- Aristarchus estimated that the Sun is 20 or so times farther from the Earth than the Moon. Since both have approximately the same angular size, the Sun must be 20 times larger than the Moon (actual value ~ 400 times)

- The largest body (the Sun) should be at the center of the solar system.

(even suggested star movement is due to Earth rotation!)
How did the Greeks explain planetary motion?

2) geocentric model:

- Earth at the center of the universe, everything orbits us.
- Heavens must be “perfect”: Objects are crystalline sphere moving on perfect spheres or in perfect circles.
Why did the ancient Greeks reject the real explanation for planetary motion?

• Argued everything would fall off the Earth if it moved.
• Inability to observe **stellar parallax** (nearby stars moving over different seasons).
The Greeks knew that the lack of observable parallax could mean one of two things:

- Stars are so far away that the seasonal movement of stellar parallax is too small to notice with the naked eye or/

- Earth does not orbit Sun; Earth is the center of the universe and the Sun orbits the Earth.

- Most Greeks rejected the correct explanation (1) because they did not think the stars could be \textit{that} far away

- \textit{Thus setting the stage for the long, historical showdown between Earth-centered and Sun-centered systems.}
What have we learned?

• What was so mysterious about planetary motion in our sky?
  – Like the Sun and Moon, planets usually drift eastward relative to the stars from night to night; but sometimes, for a few weeks or few months, a planet turns westward in its apparent retrograde motion.

• Why did the ancient Greeks reject the real explanation for planetary motion?
  – Most Greeks concluded that Earth must be stationary, because they thought the stars could not be so far away as to make parallax undetectable.
The most sophisticated geocentric model was that of Ptolemy (A.D. 100-170) — the Ptolemaic model:

- Sufficiently accurate to remain in use for 1,500 years.
- Arabic translation of Ptolemy’s work named *Almagest*
So how does the Ptolemaic model explain retrograde motion? Planets *really do* go backward in this model.
The Copernican Revolution

Our goals for learning:

• How did Copernicus, Tycho, and Kepler challenge the Earth-centered idea?

• How did Galileo solidify the Copernican revolution?

• What are Kepler’s three laws of planetary motion?
Occam's Razor - 14th Century

- William Ockham (c. 1295–1349) Franciscan friar and logician.
- Principal says "entities should not be multiplied beyond necessity." This means:
  - any explanation of an observation should make as few assumptions as possible, "shaving off", any that make no difference.
  - when given two equally valid explanations for an observation, one should embrace the simpler idea.
How did Copernicus challenge the Earth-centered idea?

Copernicus (1473-1543)

• Proposed Sun-centered model in 1543.
• Created a simpler model than Ptolomaic. Plus a simple explanation for retrograde motion.

But . . .

Model was no more accurate than Ptolemaic model in predicting planetary positions, because it still used perfect circles.
How did Galileo solidify the Copernican revolution?

Galileo (1564-1642) overcame major objections to Copernican view.

Three key objections rooted in Aristotelian view were:

• Earth could not be moving because objects in air would be left behind.
• Non-circular orbits are not “perfect” as heavens should be.
• If Earth were really orbiting Sun, we’d detect stellar parallax.
• Galileo overcame each issue by testing each one for accuracy or fallacy. If the objection could be demonstrated to not fit further observations then it had to be discarded for something else.

• This is the start of the use of the “scientific method”
Science is a method for learning about nature.

The scientific method works like this:
- Observation
- Hypothesis (Why)
- Prediction
- Test
- All scientific knowledge is provisional, (could be proved wrong at any time).
- Scientific theories must be able to be falsified and rejected.
- This is how science progresses.
• How can we distinguish science from nonscience?

• Modern science seeks explanations for observed phenomena that rely solely on natural causes. (A scientific model cannot include divine intervention)

• Science progresses through the creation and testing of models of nature that explain the observations as simply as possible. (Simplicity = “Occam’s razor”)

• A scientific model must make testable predictions about natural phenomena that would force us to revise or abandon the model if the predictions do not agree with observations.
Thought Question:
What is the difference between the word *theory* as used in everyday speech, and the word *theory* as used in science?

A. Theory, in common speech, is something uncertain ("It’s just a theory")

B. A *scientific* theory is different. It has been thoroughly tested

C. A *scientific* theory must be discarded if it fails to explain what is observed in any experiment

D. All of the above
• How did Galileo use the scientific method to disprove the ideas of the Ptolemy model?

• Galileo tested the 3 core issues of the Ptolemy model against observations.

• If the objection could be demonstrated to not fit further observations then it had to be discarded for something else.
Galileo’s experiments showed that objects in air would stay with a moving Earth.

- Aristotle thought that all objects naturally come to rest.
- Galileo showed that objects will stay in motion unless a force acts to slow them down (Newton’s first law of motion).
Overcoming the second objection
(heavens should be perfect spheres):

Using his telescope, Galileo saw:

• Sunspots on Sun ("imperfections")
• Mountains and valleys on the Moon (proving it is not a perfect sphere)
• 'Cuphandles' around Saturn

These are observations of an imperfect universe, not presumptions from a model.
Galileo also saw four moons orbiting Jupiter, proving that not all objects orbit the Earth.

Published in a book the *Siderius Nuncius* 1610
Overcoming the third objection

(If Earth were really orbiting the Sun, then we would detect stellar parallax):

• Galileo showed stars must be much farther than anyone thought — in part by using his telescope to see the Milky Way is countless individual stars.

• If stars were much farther away, then lack of detectable parallax isn't a problem any more.
Competing models for the phases of Venus

Geocentric

Heliocentric

Competing models for the phases of Venus
Phases of Venus detectable through a telescope
Galileo observed the phases of Venus, compared them to the two competing models and concluded that the heliocentric model matched better to his data.

-Scientific Method in action!
Galileo demonstrated that the Ptolomaic model was fundamentally incorrect.

The model could not accurately predict the position of the planets - not because of bad observations, but because the concepts underpinning it were bad.

A wrong model cannot yield right answers!
Galileo Galilei

Full results published in 1632. The Catholic Church ordered Galileo to recant his claim that Earth orbits the Sun in 1633.

His book on the subject was removed from the Church’s index of banned books in 1824.

Galileo was formally vindicated by the Church in 1992.
What have we learned?

• What was the Copernican revolution?
  – Copernicus proposed a simpler model of the universe (a Sun-centered one) to explain retrograde motion of planets

• What was Galileo’s role in solidifying the Copernican revolution?
  – His experiments and observations overcame the remaining objections to the Sun-centered solar system

• What is the scientific method?
  – forming explanations for an observation then try to disprove each one with testing. The un-disproved idea goes forward.
Meanwhile, in northern Europe were Tycho Brahe and Johannes Kepler ....
Tycho Brahe (1546-1601)
Greatest Naked Eye Astronomer

• Compiled the most accurate (one arcminute) naked eye measurements ever made of planetary positions.

• Tycho’s observations of comet and a supernova challenged perfect universe idea.

• Still could not detect stellar parallax, and thus still thought Earth must be at center of solar system (but recognized that other planets go around Sun)

• Hired Kepler, who used Tycho’s observations to discover the truth about planetary motion.
Johannes Kepler
(1571-1630)

Kepler believed the orbits of each planet were encased in perfect geometric shapes, such as dodecahedrons!
• Kepler first tried to match Tycho’s observations with circular orbits

• But an 8-arcminute discrepancy led him eventually to ellipses and 3 laws of planetary motion.

“If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy.”
What is an ellipse?

An ellipse looks like an elongated circle
Eccentricity of an Ellipse
What are 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.
Earth's Orbit

Earth's orbit is only slightly eccentric.

Circular orbit with same semimajor axis, centered on Sun.

\[ e = 0.017 \]

1 AU

Sun
Kepler’s Second Law: As a planet moves around its orbit, it sweeps out equal areas in equal times.

⇒ 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
- \( a \) = avg. distance from Sun in AU
Thought Question:
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 $p^2 = a^3$
What have we learned?

• How did Copernicus, Tycho and Kepler challenge the Earth-centered idea?
  – Copernicus created a sun-centered model; Tycho provided the data needed to improve this model; Kepler found a model that fit Tycho’s data

• What are Kepler’s three laws of planetary motion?
  – 1. The orbit of each planet is an ellipse with the Sun at one focus
  – 2. As a planet moves around its orbit it sweeps our equal areas in equal times
  – 3. More distant planets orbit the Sun at slower average speeds: $p^2 = a^3$