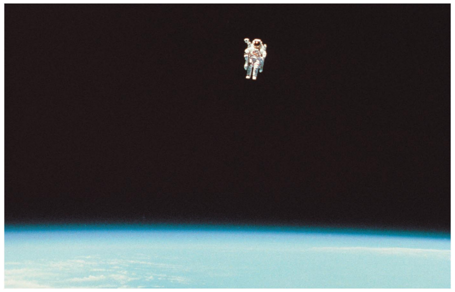
Chapter 3
The Science of Astronomy



3.1 The Ancient Roots of Science

Our goals for learning:

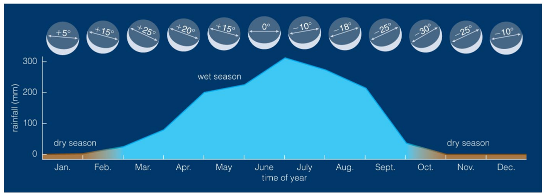
- In what ways do all humans employ scientific thinking?
- How did astronomical observations benefit ancient societies?
- What did ancient civilizations achieve in astronomy?

In what ways do all humans employ scientific thinking?

- Scientific thinking is based on everyday ideas of observation and trial-and-error experiments.

How did astronomical observations benefit ancient societies?

- Keeping track of time and seasons
  - for practical purposes, including agriculture
  - for religious and ceremonial purposes
- Aid to navigation



Ancient people of central Africa (6500 BC) could predict seasons from the orientation of the crescent moon

Table 3.1 The Seven Days of the Week and the Astronomical Objects They Honor

The correspondence between objects and days is easy to see in French and Spanish. In English, the correspondence becomes clear when we look at the names of the objects used by the Teutonic tribes who lived in the region of modern-day Germany.

Object	*Teutonic Name*	*English*	*French*	*Spanish*
Sun	Sun	Sunday	dimanche	domingo
Moon	Moon	Monday	lundi	lunes
Mars	Tiw	Tuesday	mardi	martes
Mercury	Woden	Wednesday	mercredi	miércoles
Jupiter	Thor	Thursday	jeudi	jueves
Venus	Fria	Friday	vendredi	viernes
Saturn	Saturn	Saturday	samedi	sábado

Days of week were named for Sun, Moon, and *visible* planets

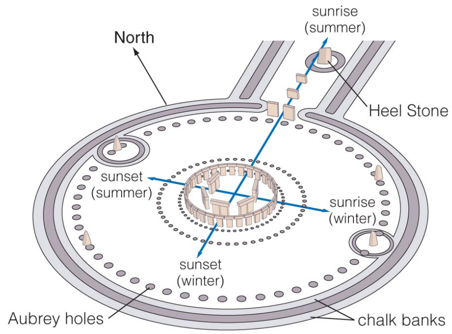
What did ancient civilizations achieve in astronomy?

- Daily timekeeping
- Tracking the seasons and calendar
- Monitoring lunar cycles
- Monitoring planets and stars
- Predicting eclipses
- And more…

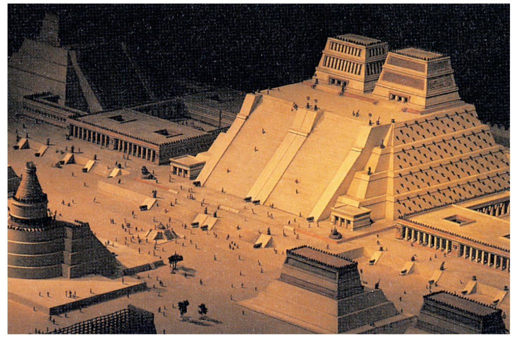
- Egyptian obelisk: Shadows tell time of day.

a The remains of Stonehenge today.

England: Stonehenge (completed around 1550 B.C.)



England: Stonehenge (1550 B.C.)



Mexico: model of the Templo Mayor

New Mexico: Anasazi kiva aligned north-south

a A single dagger of sunlight pierces the center of the carved spiral only at noon on the summer solstice.

SW United States: "Sun Dagger" marks summer solstice

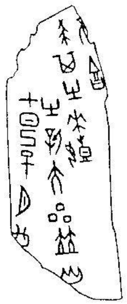
Scotland: 4,000-year-old stone circle; Moon rises as shown here every 18.6 years.

Peru: Lines and patterns, some aligned with stars.

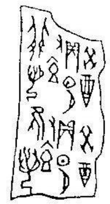
Macchu Pichu, Peru: Structures aligned with solstices.

South Pacific: Polynesians were very skilled in art of celestial navigation

France: Cave paintings from 18,000 B.C. may suggest knowledge of lunar phases (29 dots)



"On the Jisi day, the 7th day of the month, a big new star appeared in the company of the Ho star."



"On the Xinwei day the new star dwindled."

Bone or tortoise shell inscription from the 14th century BC.

China: Earliest known records of supernova explosions (1400 B.C.)

What have we learned?

- In what ways do all humans employ scientific thinking?
  - Scientific thinking involves the same type of trial and error thinking that we use in our everyday live, but in a carefully organized way.
- How did astronomical observations benefit ancient societies?
  - Keeping track of time and seasons; navigation

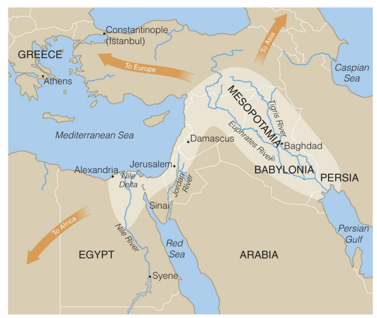
What have we learned?

- What did ancient civilizations achieve in astronomy?
  - To tell the time of day and year, to track cycles of the Moon, to observe planets and stars. Many ancient structures aided in astronomical observations.

3.2 Ancient Greek Science

Our goals for learning:

- Why does modern science trace its roots to the Greeks?
- How did the Greeks explain planetary motion?
- How was Greek knowledge preserved through history?



Our mathematical and scientific heritage originated with the civilizations of the Middle East

Artist's reconstruction of Library of Alexandria

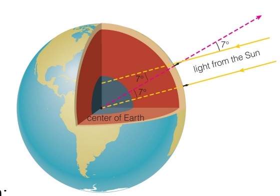
Why does modern science trace its roots to the Greeks?

Greek geocentric model (c. 400 B.C.)

- Greeks were the first people known to make ***models*** of nature.
- They tried to explain patterns in nature without resorting to myth or the supernatural.

Special Topic: Eratosthenes measures the Earth (c. 240 BC)

<u>Measurements:</u>
Syene to Alexandria
distance ≈ 5000 stadia
angle = 7°

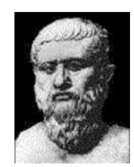


<u>Calculate circumference of Earth:</u>
7/360 × (circum. Earth) = 5000 stadia
⇒ circum. Earth = 5000 × 360/7 stadia ≈ 250,000 stadia

<u>Compare to modern value (≈ 40,100 km):</u>
Greek stadium ≈ 1/6 km ⇒ 250,000 stadia ≈ 42,000 km

How did the Greeks explain planetary motion?

Underpinnings of the Greek geocentric model:

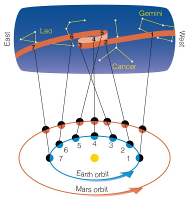


Plato

- Earth at the center of the universe
- Heavens must be "perfect": Objects moving on perfect spheres or in perfect circles.

Aristotle

But this made it difficult to explain apparent retrograde motion of planets…



Interactive Figure

Review: Over a period of 10 weeks, Mars appears to stop, back up, then go forward again.

Ptolemy

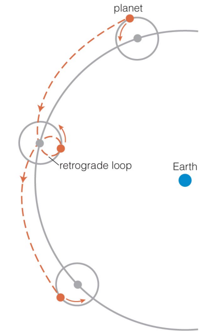
The most sophisticated geocentric model was that of Ptolemy (A.D. 100-170) — the **Ptolemaic model:**

• Sufficiently accurate to remain in use for 1,500 years.

• Arabic translation of Ptolemy's work named *Almagest* ("the greatest compilation")

c A woodcutting of Ptolemy holding a cross-staff (artist unknown).

So how does the Ptolemaic model explain retrograde motion? Planets *really do* go backward in this model..



Interactive Figure

Thought Question

Which of the following is NOT a fundamental difference between the geocentric and Sun-centered models of the solar system?

A. Earth is stationary in the geocentric model but moves around Sun in Sun-centered model.
B. Retrograde motion is real (planets really go backward) in geocentric model but only apparent (planets don't really turn around) in Sun-centered model.
C. Stellar parallax is expected in the Sun-centered model but not in the Earth-centered model.
D. The geocentric model is useless for predicting planetary positions in the sky, while even the earliest Sun-centered models worked almost perfectly.

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How was Greek knowledge preserved through history?

• Muslim world preserved and enhanced the knowledge they received from the Greeks

• Al-Mamun's House of Wisdom in Baghdad was a great center of learning around A.D. 800

• With the fall of Constantinople (Istanbul) in 1453, Eastern scholars headed west to Europe, carrying knowledge that helped ignite the European Renaissance.

What have we learned?

- Why does modern science trace its roots to the Greeks?
  - They developed models of nature and emphasized that the predictions of models should agree with observations
- How did the Greeks explain planetary motion?
  - The Ptolemaic model had each planet move on a small circle whose center moves around Earth on a larger circle

What have we learned?

- How was Greek knowledge preserved through history?
  - While Europe was in its Dark Ages, Islamic scientists preserved and extended Greek science, later helping to ignite the European Renaissance

3.3 The Copernican Revolution

Our goals for learning:

- How did Copernicus, Tycho, and Kepler challenge the Earth-centered idea?
- What are Kepler's three laws of planetary motion?
- How did Galileo solidify the Copernican revolution?

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

Copernicus (1473-1543):

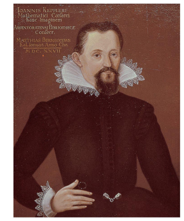
- Proposed Sun-centered model (published 1543)
- Used model to determine layout of solar system (planetary distances in AU)

But . . .

- Model was no more accurate than Ptolemaic model in predicting planetary positions, because it still used perfect circles.

Tycho Brahe (1546-1601)

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

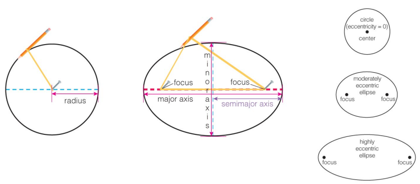


Johannes Kepler (1571-1630)

- Kepler first tried to match Tycho's observations with circular orbits
- But an 8-arcminute discrepancy led him eventually to ellipses…

"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."

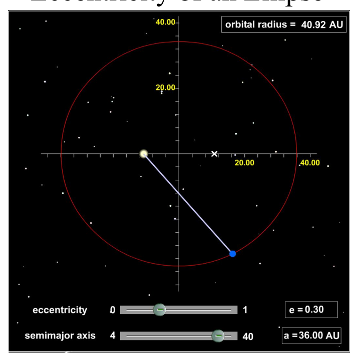
What is an ellipse?



Interactive Figure

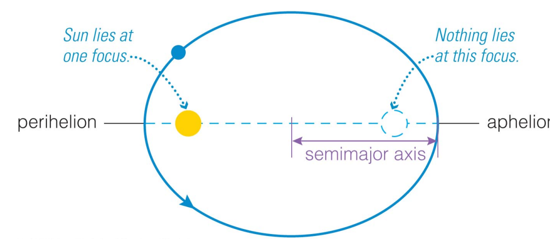
An ellipse looks like an elongated circle

Eccentricity of an Ellipse

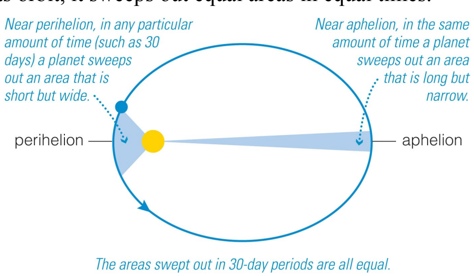


What are Kepler's three laws of planetary motion?

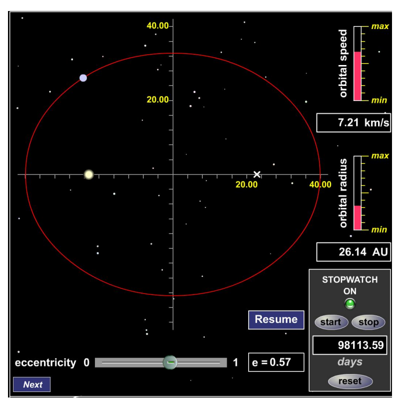
Kepler's First Law: The orbit of each planet around the Sun is an ***ellipse*** with the Sun at one focus.



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.



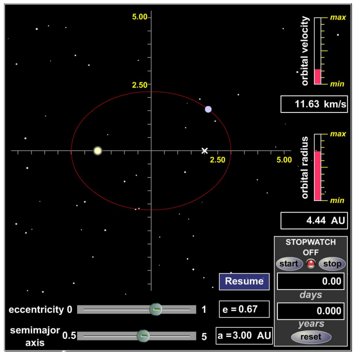
Kepler's Third Law

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

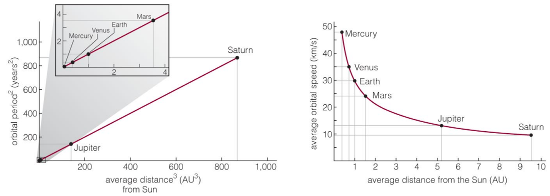
$$p^2 = a^3$$

p = orbital period in years
a = avg. distance from Sun in AU

Kepler's Third Law



Graphical version of Kepler's Third Law



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 $p^2 = a^3$

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

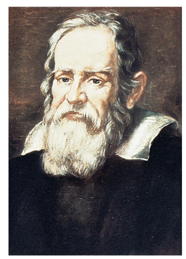
A. 4 years
B. 8 years
C. 16 years
D. 64 years

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

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

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

How did Galileo solidify the Copernican revolution?



Galileo (1564–1642)

Galileo (1564-1642) overcame major objections to Copernican view. Three key objections rooted in Aristotelian 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.

Overcoming the first objection (nature of motion):

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).

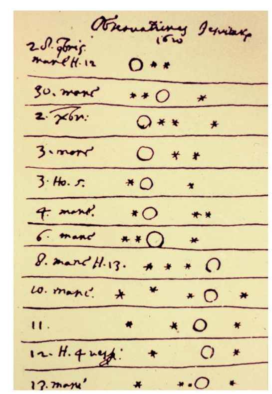
Overcoming the second objection (heavenly perfection):

- Tycho's observations of comet and supernova already challenged this idea.
- Using his telescope, Galileo saw:
  - Sunspots on Sun ("imperfections")
  - Mountains and valleys on the Moon (proving it is not a perfect sphere)

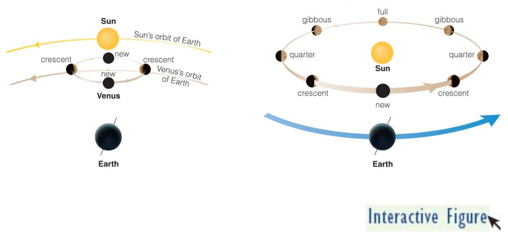
Overcoming the third objection (parallax):

- Tycho *thought* he had measured stellar distances, so lack of parallax seemed to rule out an orbiting Earth.
- Galileo showed stars must be much farther than Tycho thought — in part by using his telescope to see the Milky Way is countless individual stars.

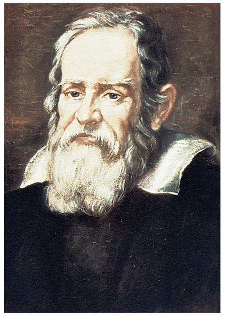
✓ If stars were much farther away, then lack of detectable parallax was no longer so troubling.



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



Galileo's observations of phases of Venus proved that it orbits the Sun and not Earth.



Galileo Galilei

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?

- 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: $p^2 = a^3$

What have we learned?

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

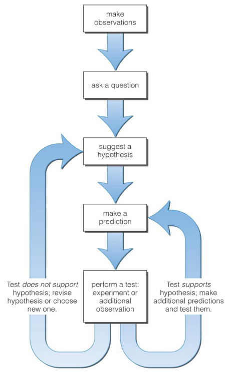
3.4 The Nature of Science

Our goals for learning:

- How can we distinguish science from nonscience?
- What is a scientific theory?

How can we distinguish science from non-science?

- Defining science can be surprisingly difficult.
- *Science* from the Latin *scientia*, meaning "knowledge."
- But not all knowledge comes from science…



The idealized scientific method

- Based on proposing and testing hypotheses
- **hypothesis** = educated guess

But science rarely proceeds in this idealized way… For example:

- Sometimes we start by "just looking" then coming up with possible explanations.
- Sometimes we follow our intuition rather than a particular line of evidence.

Hallmarks of Science: #1

Modern science seeks explanations for observed phenomena that rely solely on natural causes.

(A scientific model cannot include divine intervention)

Hallmarks of Science: #2

Science progresses through the creation and testing of models of nature that explain the observations as simply as possible.

(Simplicity = "Occam's razor")

Hallmarks of Science: #3

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.

What is a scientific theory?

- The word theory has a different meaning in science than in everyday life.
- 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, AND
  - —Must be supported by a large, compelling body of evidence.
  - —Must NOT have failed any crucial test of its validity.

Thought Question

Darwin's theory of evolution meets all the criteria of a scientific theory. This means:

A. Scientific opinion is about evenly split as to whether evolution really happened.
B. Scientific opinion runs about 90% in favor of the theory of evolution and about 10% opposed.
C. After more than 100 years of testing, Darwin's theory stands stronger than ever, having successfully met every scientific challenge to its validity.
D. There is no longer any doubt that the theory of evolution is absolutely true.

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What have we learned?

- How can we distinguish science from non-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

3.5 Astrology

Our goals for learning:

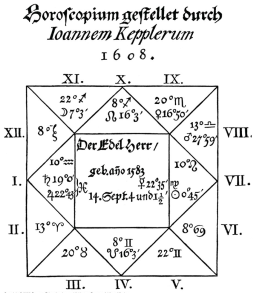
- How is astrology different from astronomy?
- Does astrology have any scientific validity?

How is astrology different from astronomy?

- Astronomy is a science focused on learning about how stars, planets, and other celestial objects work.
- Astrology is a search for hidden influences on human lives based on the positions of planets and stars in the sky.

Does astrology have any scientific validity?

- Scientific tests have shown that astrological predictions are no more accurate than we should expect from pure chance.



What have we learned?

- How is astrology different from astronomy?
  - Astronomy is the scientific study of the universe and the celestial objects within it.
  - Astrology assumes that the positions of celestial objects influence human events.
- Does astrology have any scientific validity?
  - Scientific tests show that the predictions of astrology are no more accurate than pure chance.