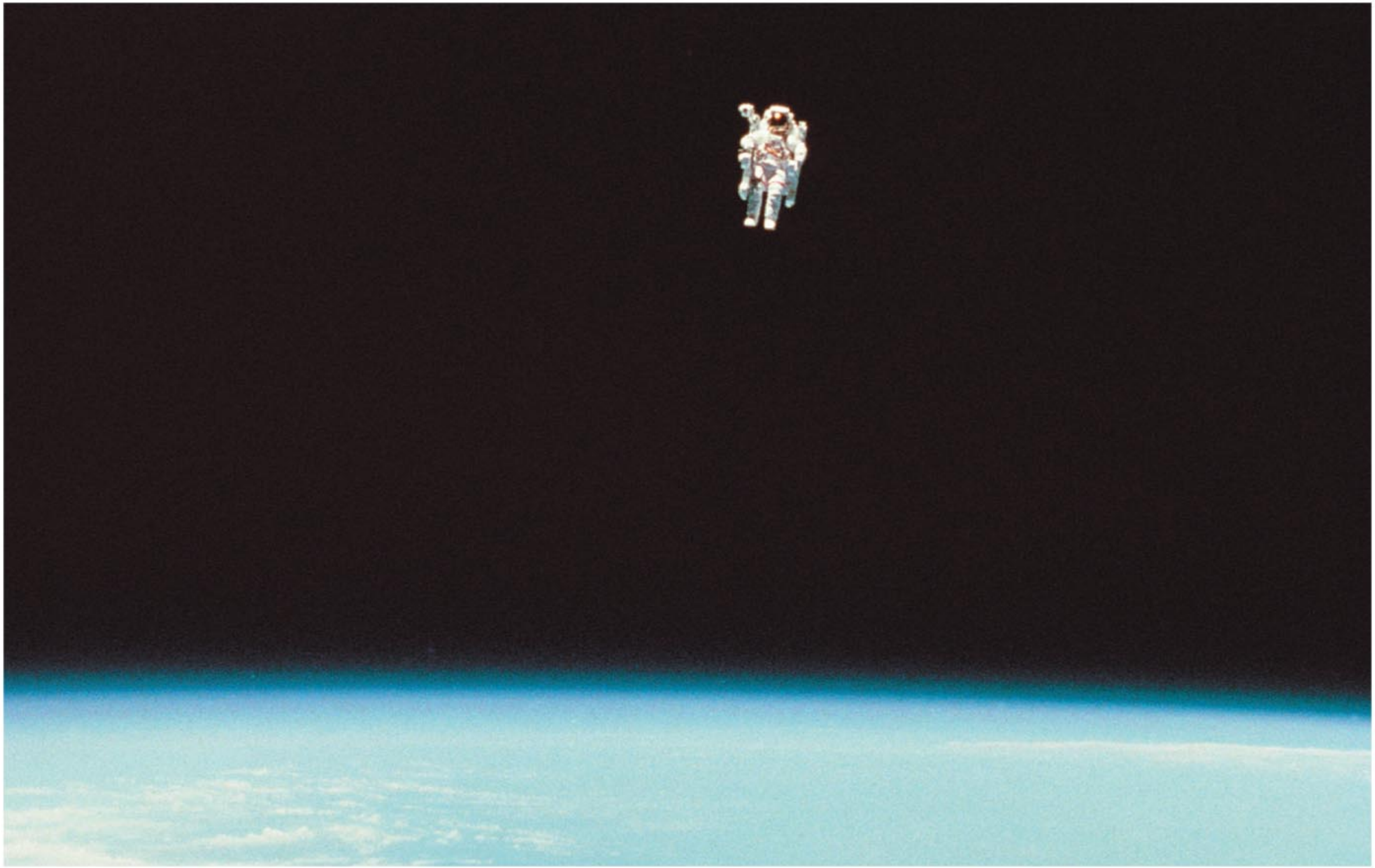
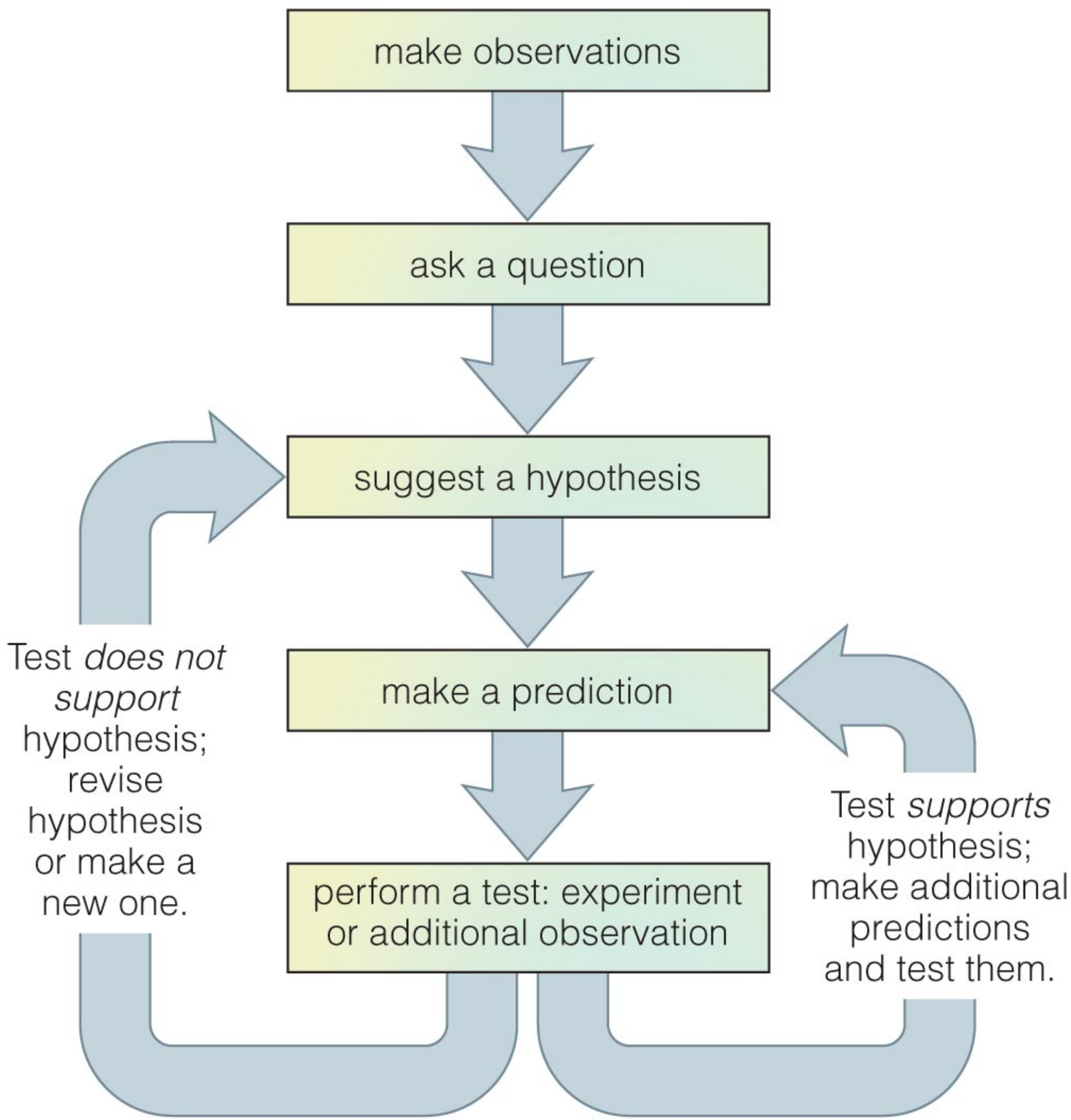
Chapter 3: The Science of Astronomy



3.1 The Ancient Roots of Science

- Our goals for learning:
  - **In what ways do all humans use scientific thinking?**
  - **How is modern science rooted in ancient astronomy?**

In what ways do all humans use scientific thinking?



- Scientific thinking is based on everyday ideas of observation and trial-and-error experiments.
- "Convince me"
- Having a high burden of proof and a clear chain of thought about how you arrive at your conclusion

Cooking and Science: Somewhat Similar

A scientific case study: 2007-2013

I try to understand what planets around other stars "are like." How hot are they, what are they made of, how do the change with time?

It was known in 2007 that some "hot Jupiters" (gas giant, Jupiter-like planets that orbit very close to their parents) had **hot upper atmospheres** and some had **cold upper atmospheres**

Whether or not the upper atmosphere is hot or cold changes the amount of **infrared light** that these planets emit

In 2008 I thought that I had figured this out

The Astrophysical Journal, 678:1419–1435, 2008 May 10

A UNIFIED THEORY FOR THE ATMOSPHERES OF THE HOT AND VERY HOT JUPITERS: TWO CLASSES OF IRRADIATED ATMOSPHERES

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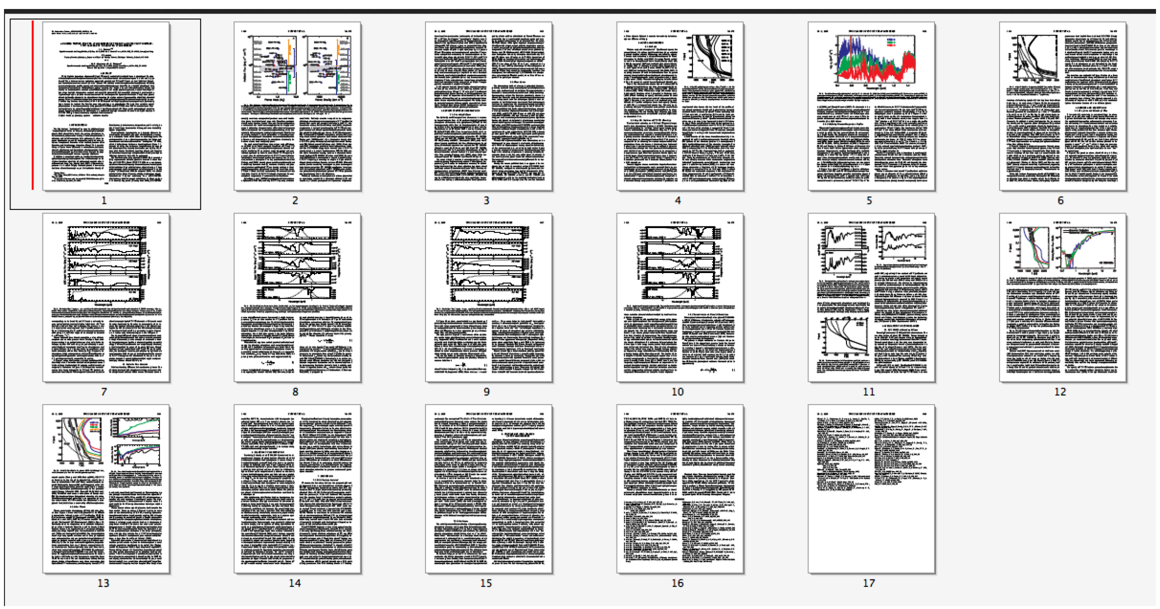
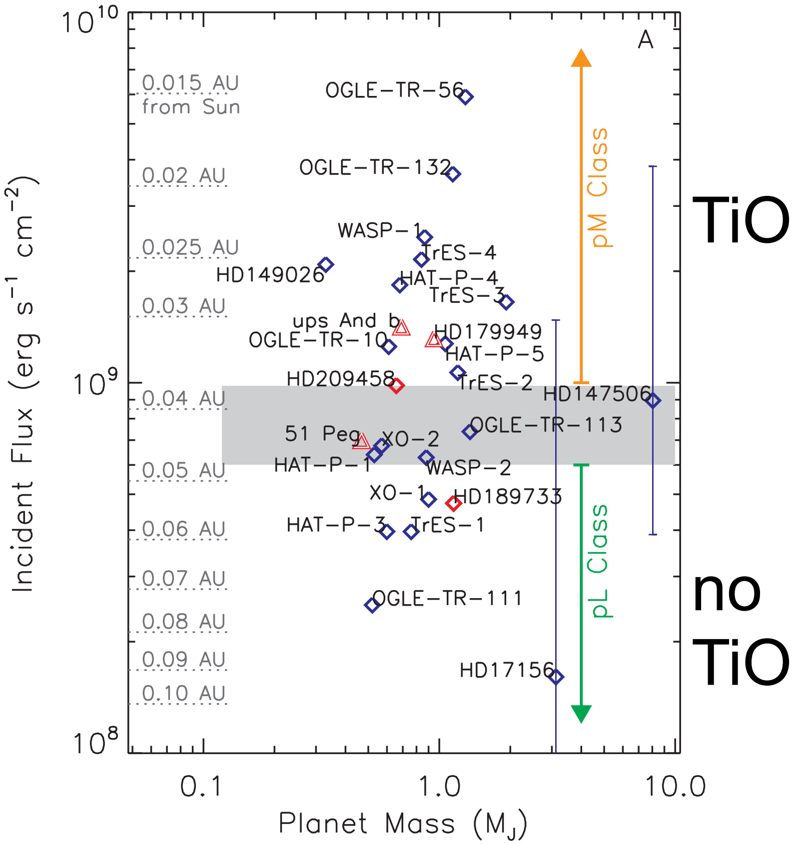
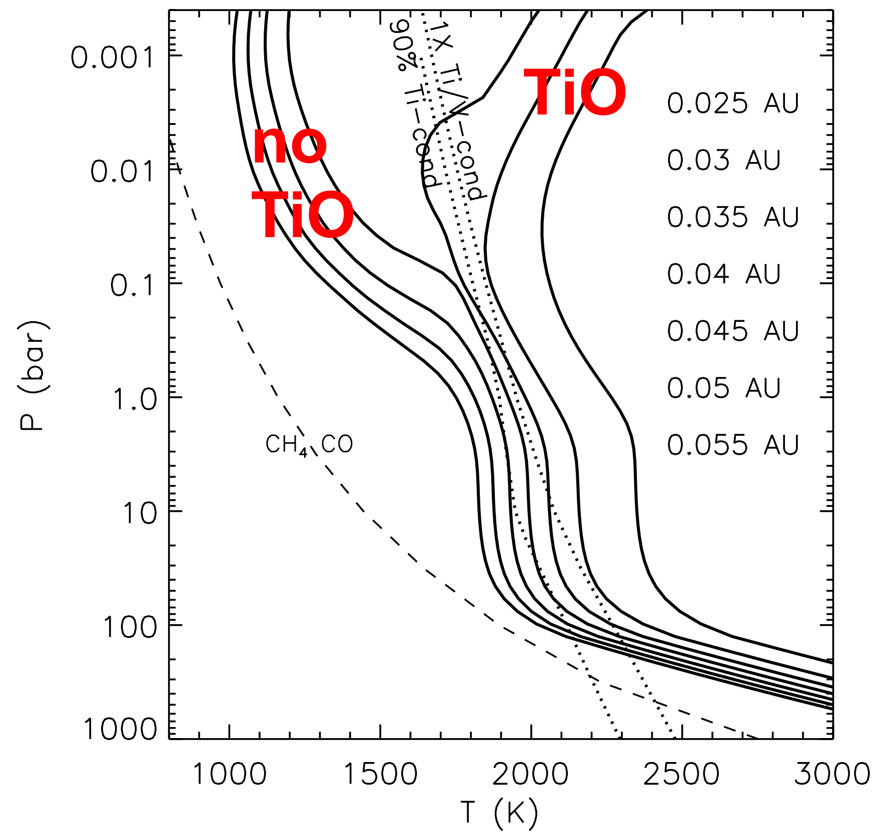


I proposed two class of "hot Jupiters"





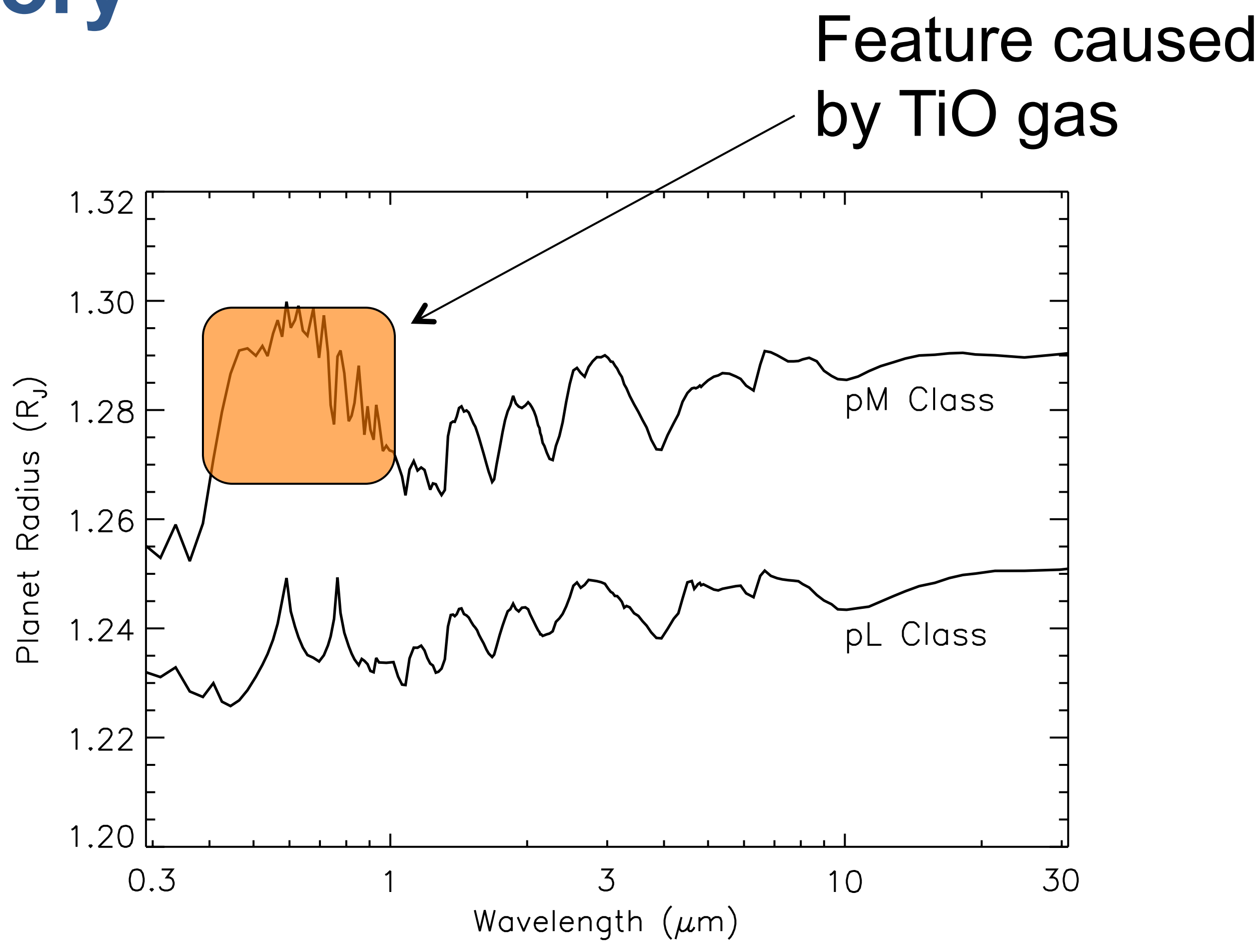
- The hottest planets have **TiO molecules** in their atmosphere, which can strongly absorb starlight at low pressures, which heats the upper atmospheres
- The colder planets should **not have this molecule** in their atmosphere, because at cold temperatures it converts to a different molecule

I discussed in a lot of detail why this theory was consistent with all observational data available at that time

Only about 4 planets had been observed by that time, but since it matched all data, one could probably call it a **theory** rather than a **hypothesis**

If there had been no data, and I had suggested how the planets would behave, then **hypothesis** might have been better

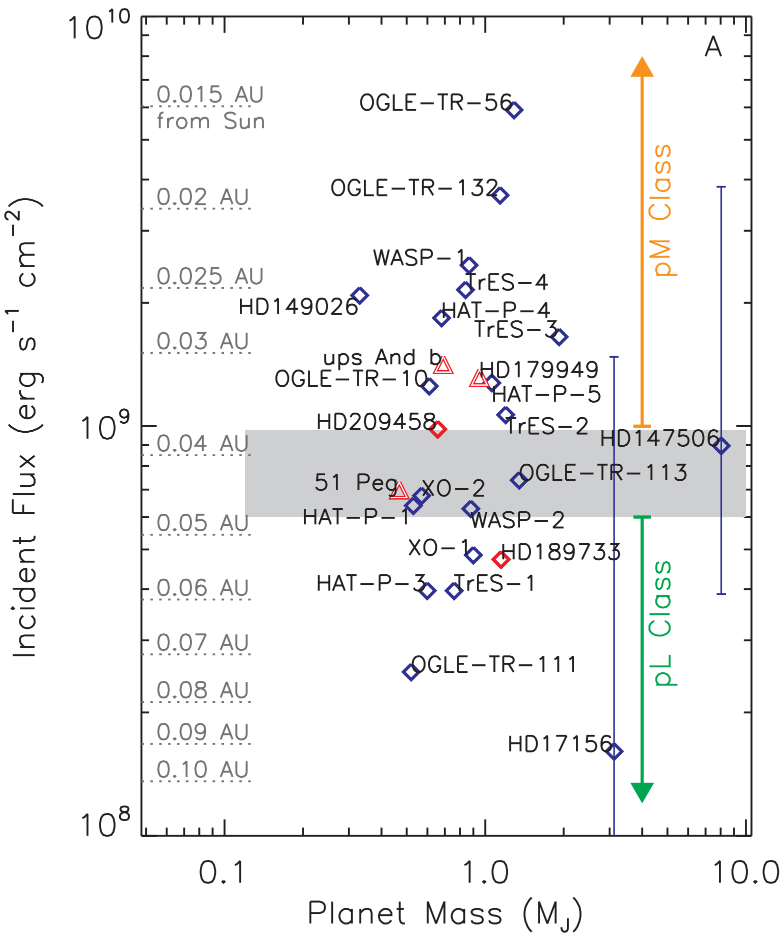
I suggested a variety of different and new observations that could confirm or refute my theory



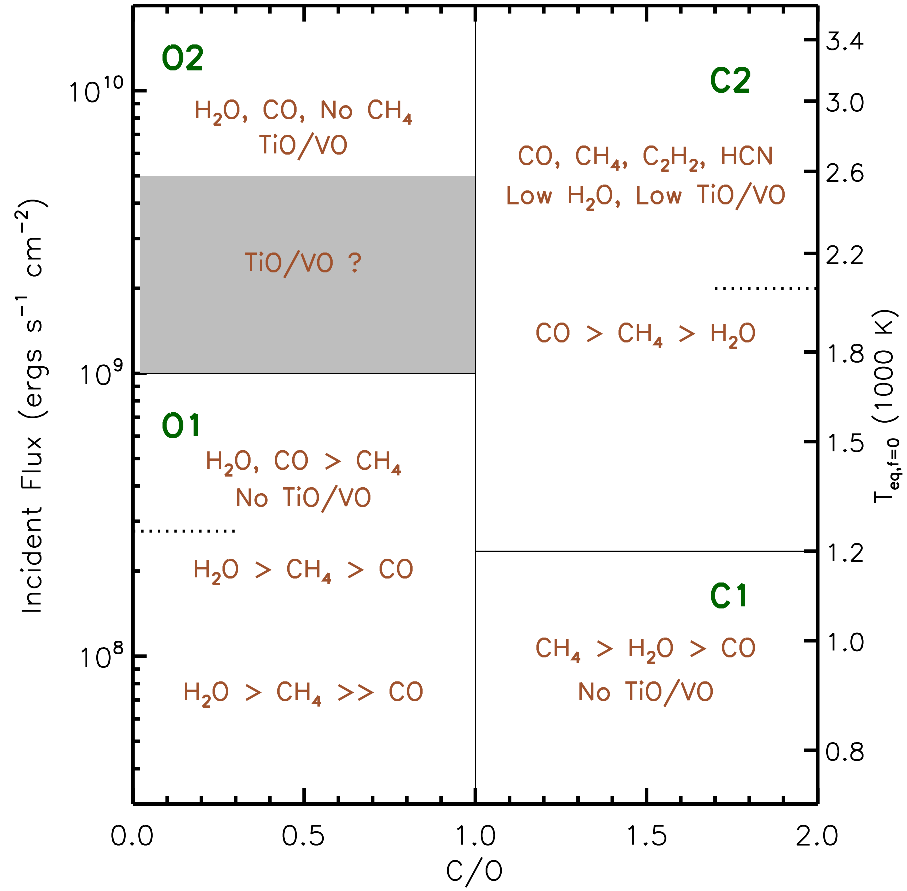
I was wrong.

- Now about 40 planets have been observed, and there is **no evidence for TiO** molecules in any planet!
- However, about 1/3 of the hot Jupiters do have a hot upper atmosphere, and we still don’t know why
  - However, some of the hot planets lack hot upper atmospheres
  - Some of the colder planets do have hot upper atmospheres
- Additional classification systems have been proposed

A potential new scheme for classification



Mine (2008)



Another (2012)

We may be stuck for awhile

- We probably need better observations to figure out what is really going on in these atmospheres
- Like in much of astronomy, and other sciences, we need new tools (the James Webb Space Telescope, launching 2018) to obtain more and better data

HST hot Jupiter transmission spectral survey: evidence for aerosols and lack of TiO in the atmosphere of WASP-12b

D. K. Sing[1⋆], A. Lecavelier des Etangs[2], J. J. Fortney[3], A. S. Burrows[4], F. Pont[1], H. R. Wakeford[1], G. E. Ballester[5], N. Nikolov[1], G. W. Henry[6], S. Aigrain[7], D. Deming[8], T. M. Evans[7], N. P. Gibson[9], C. M. Huitson[1], H. Knutson[10], A. P. Showman[7], A. Vidal-Madjar[2], P. A. Wilson[1], M. H. Williamson[5], K. Zahnle[11]

Science is Fluid

- Some theories have passed every test for 100 years, but people keep thinking of new and unique tests
  - Einstein's theories of relativity
  - Darwin's theory of natural selection
- Some knowledge gained from science, if it has passed tests for a very long time, **is extremely likely** to be a real finding of how the world works
  - *We KNOW it works because otherwise engineers wouldn't be able to make things*
- Some knowledge gained from science has not **YET** been diligently tested for a long time, and is subject to change

Science in other fields

- While I personally can’t verify findings in other fields (galaxies, biochemistry) I know these fields use a similar scientific process so that I can be **appropriately confident** in the results, based on how new or well-tested the results are

- The things you will learn in our class range from “iron-clad correct,” like Kepler’s laws, to provisional understandings based on the latest observations and discussions

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?**

3.2 Ancient Greek Science

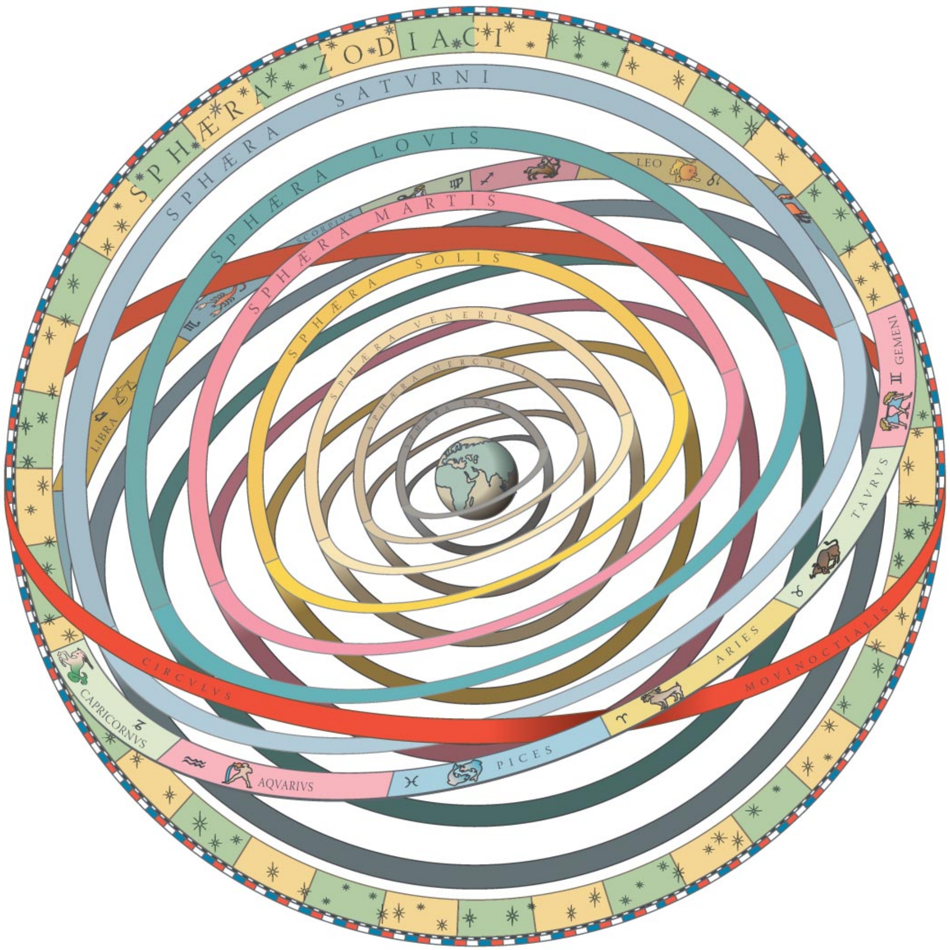
a This rendering shows an artist's reconstruction of the Great Hall of the ancient Library of Alexandria.

b A rendering similar to part a, showing a scroll room in the ancient library.

c The New Library of Alexandria in Egypt, which opened in 2003.

- Artist's reconstruction of the Library of Alexandria.

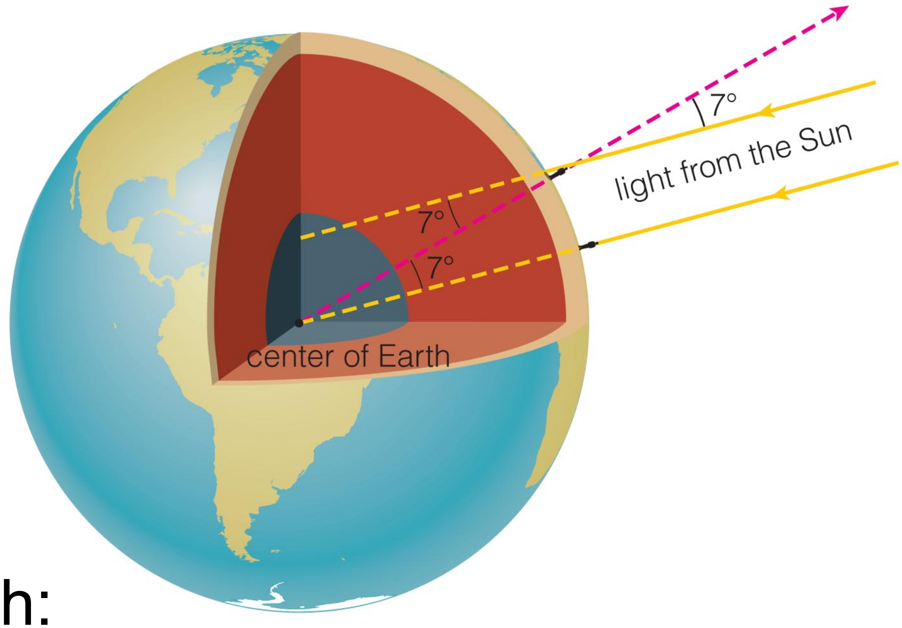
Why does modern science trace its roots to the Greeks?



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 Earth (c. 240 B.C.)



Measurements:

Syene to Alexandria

distance ≈ 5000 stadia

angle = 7°

Calculate circumference of Earth:

7/360 × (circum. Earth) = 5000 stadia

⇒ circum. Earth = 5000 × 360/7 stadia ≈ 250,000 stadia

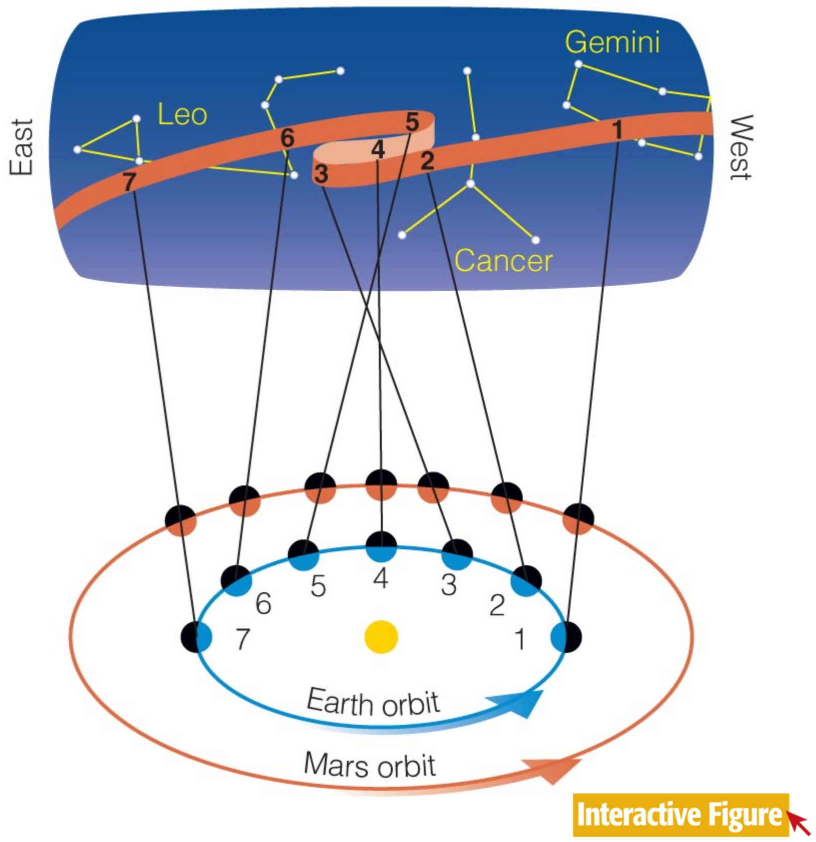
Compare to modern value (≈ 40,100 km):

Greek stadium ≈ 1/6 km ⇒ 250,000 stadia ≈ 42,000 km

How did the Greeks explain planetary motion?

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

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



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

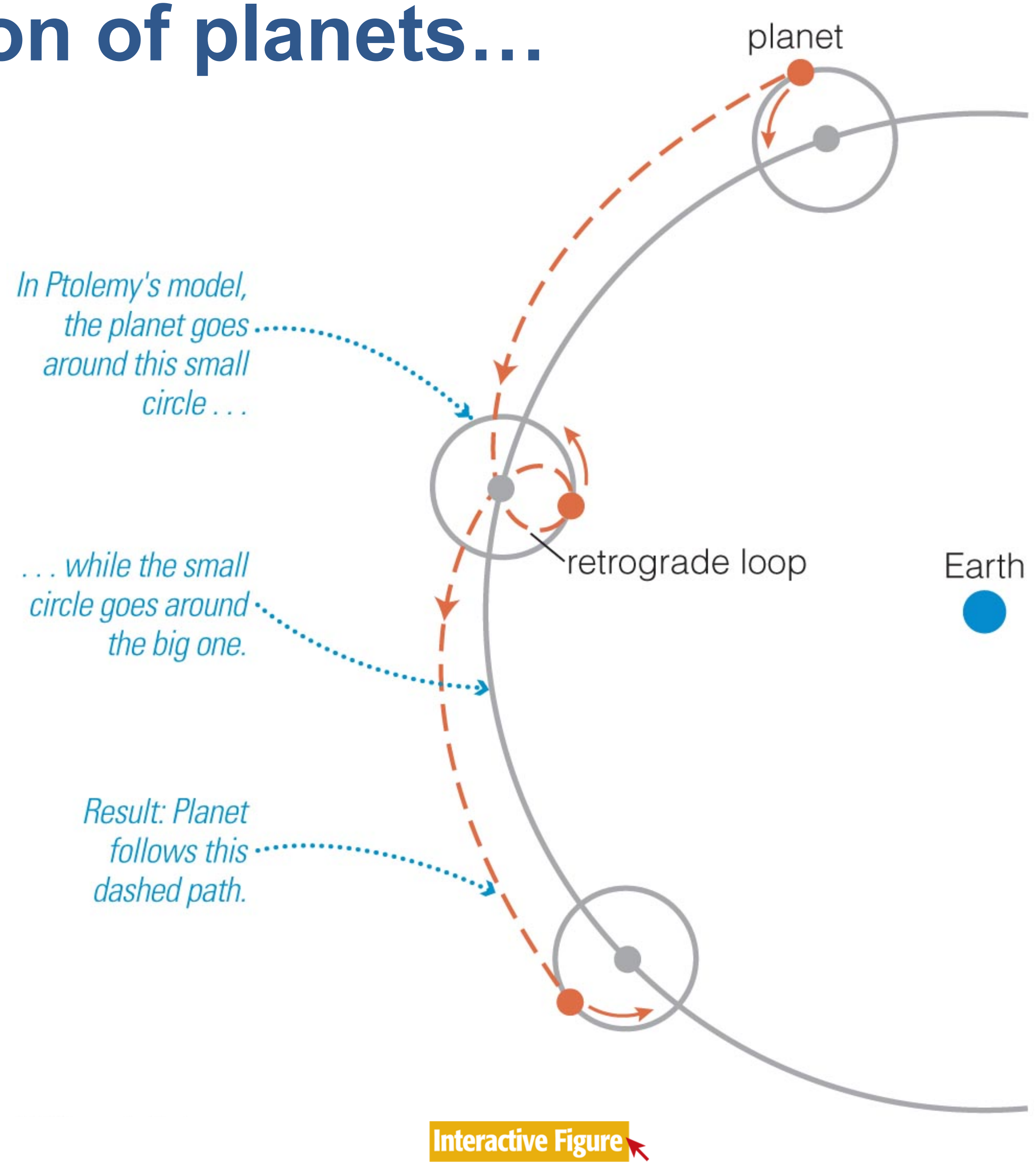
But this made it difficult to explain apparent retrograde motion of planets…

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")

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

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



How was Greek knowledge preserved through history?

- The 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.

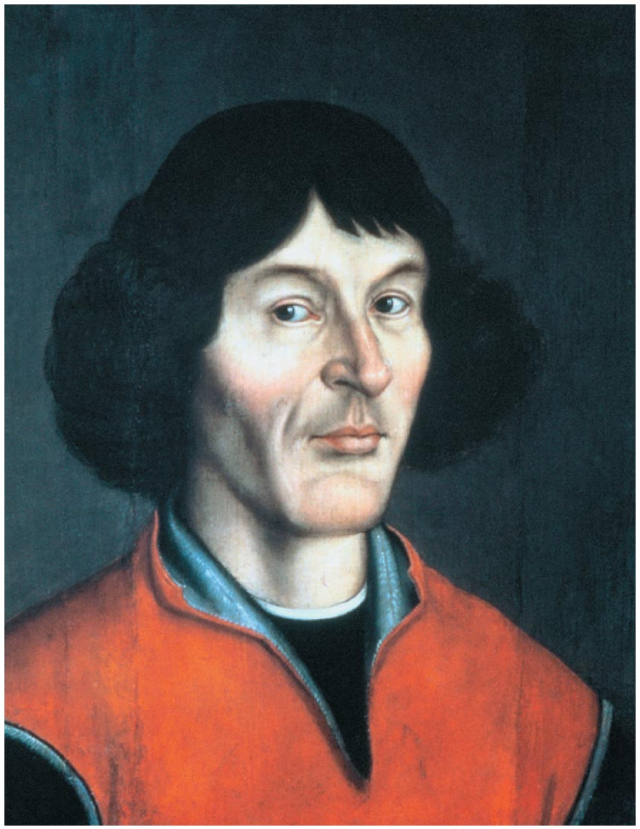
What have we learned?

- **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.

3.3 The Copernican Revolution

- Our goals for learning:
  - **How did Copernicus, Tycho, and Kepler challenge the Earth-centered model?**
  - **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 model?



Copernicus (1473-1543)

- Proposed a Sun-centered model (published 1543)
- Used model to determine layout of solar system (planetary distances in AU) But . . .
- The model was no more accurate than the Ptolemaic model in predicting planetary positions, because it still used perfect circles.

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

Tycho Brahe (1546-1601)

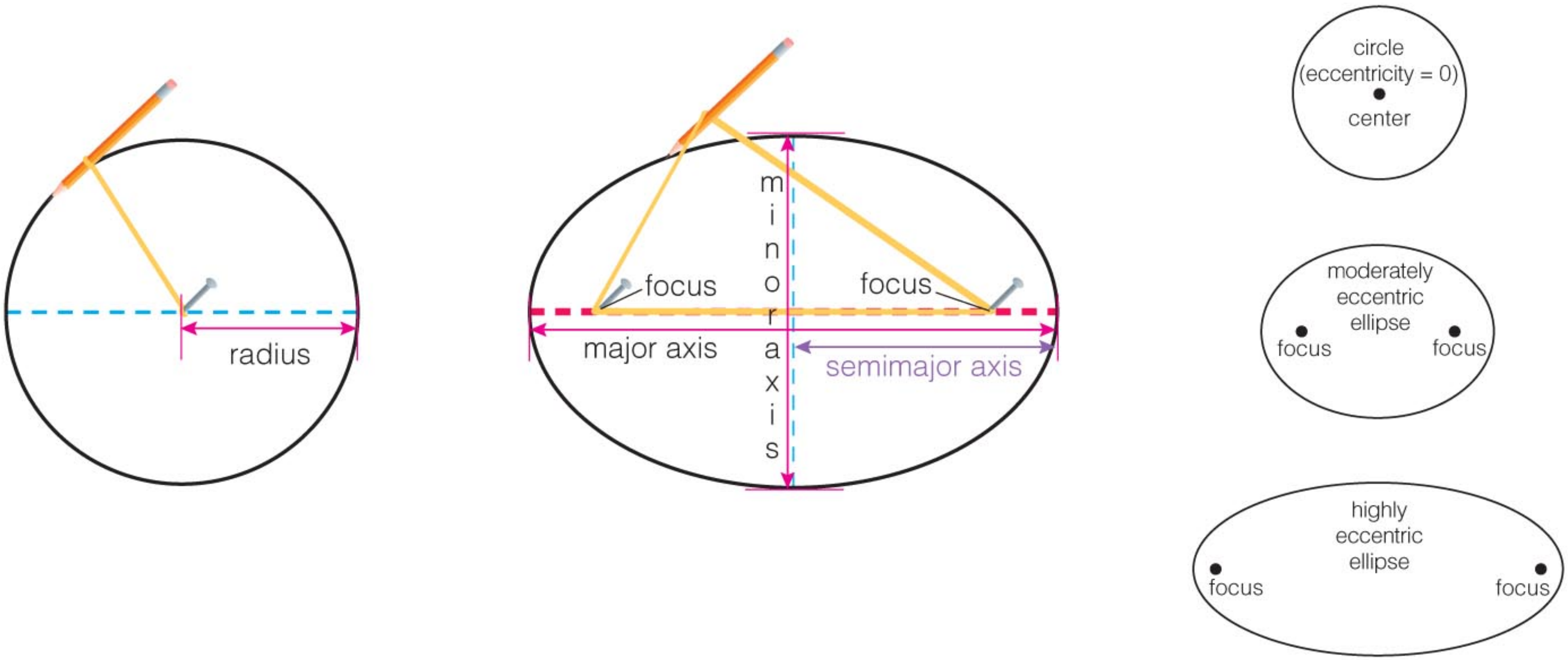
- Compiled the most accurate (one arcminute) naked eye measurements ever made of planetary positions.
- Still could not detect stellar parallax, and thus still thought Earth must be at center of solar system (but recognized that other planets go around Sun).
- Hired Kepler, who used Tycho's observations to discover the truth about planetary motion.

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

Johannes Kepler
(1571-1630)

- Kepler first tried to match Tycho's observations with circular orbits
- But small discrepancies 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?



a Drawing a circle with a string of fixed length.

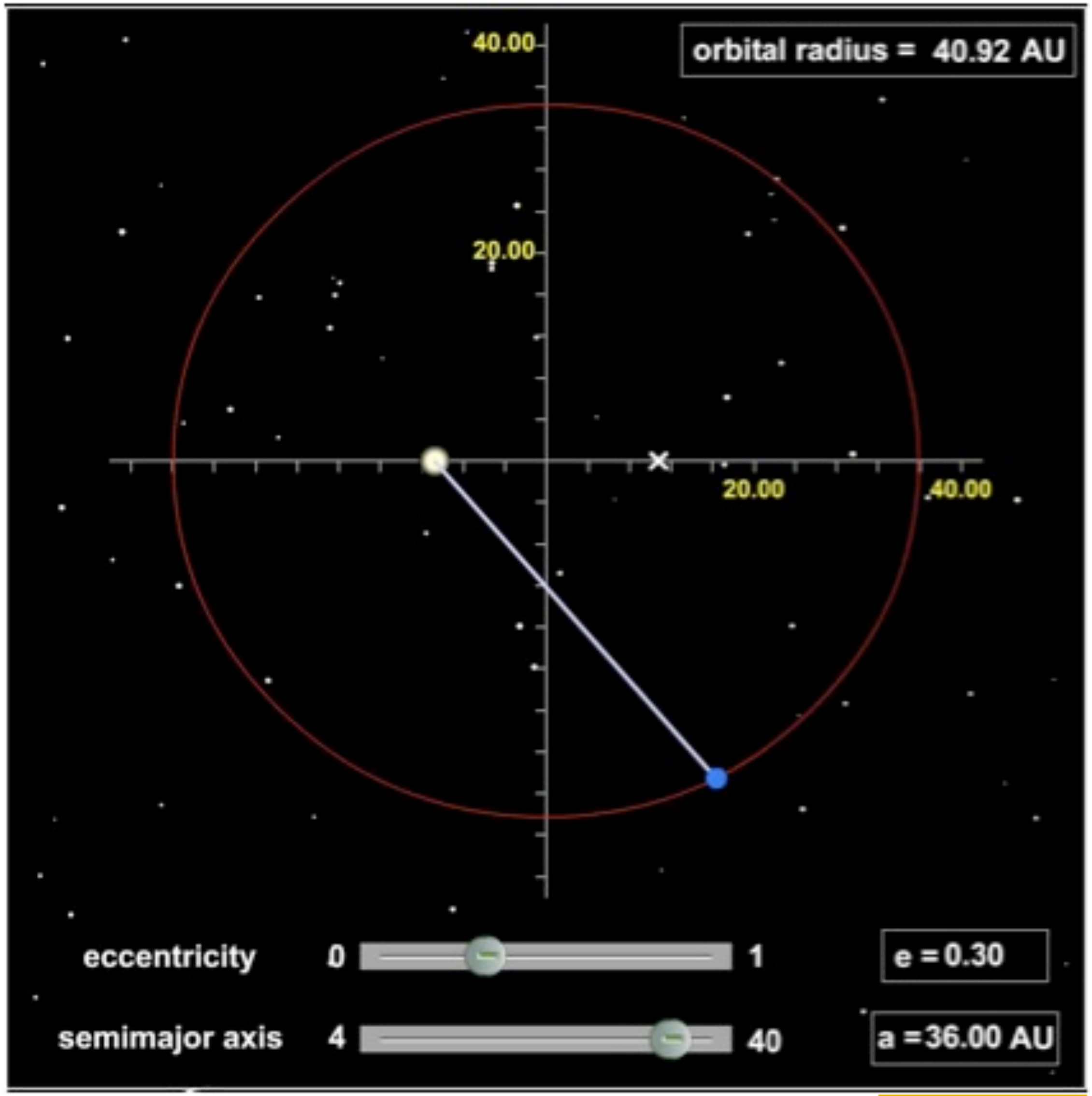
b Drawing an ellipse with a string of fixed length.

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

Interactive Figure

An ellipse looks like an elongated circle.

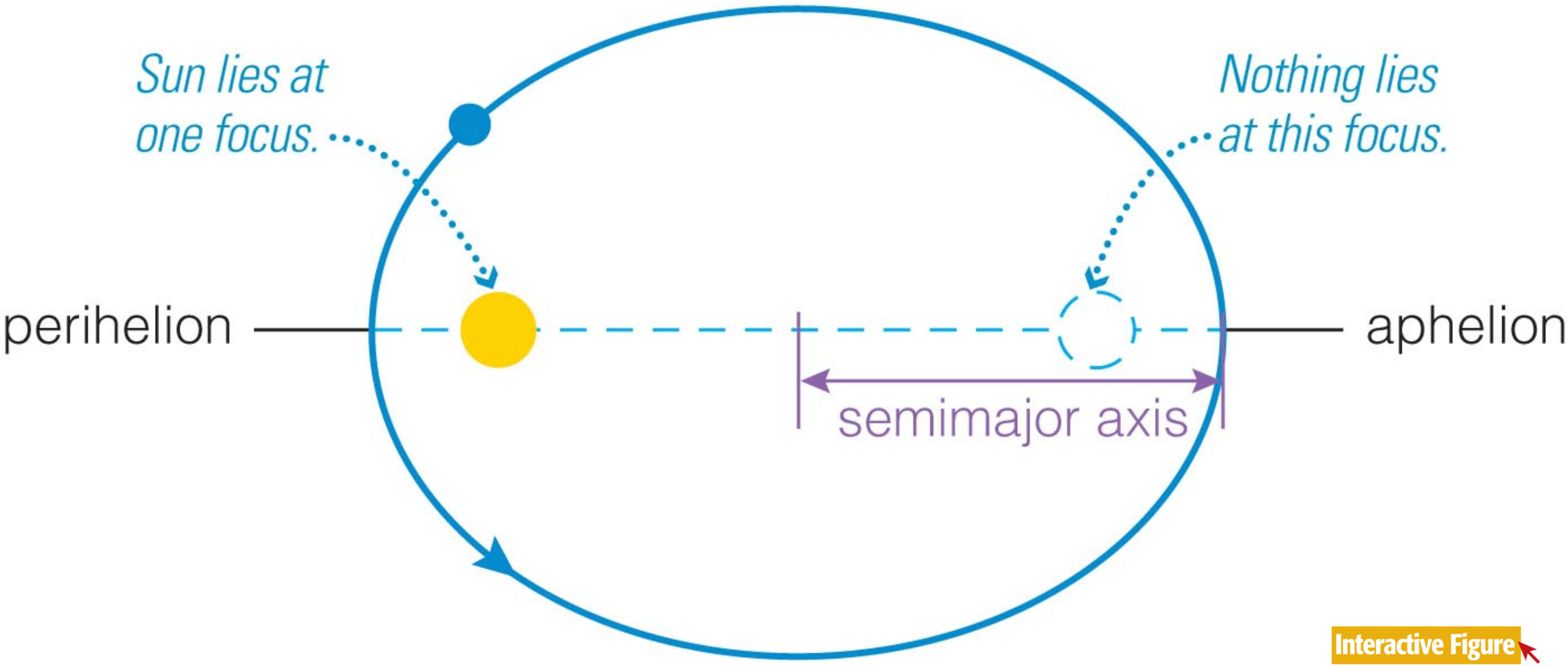
Eccentricity of an Ellipse



Interactive Figure

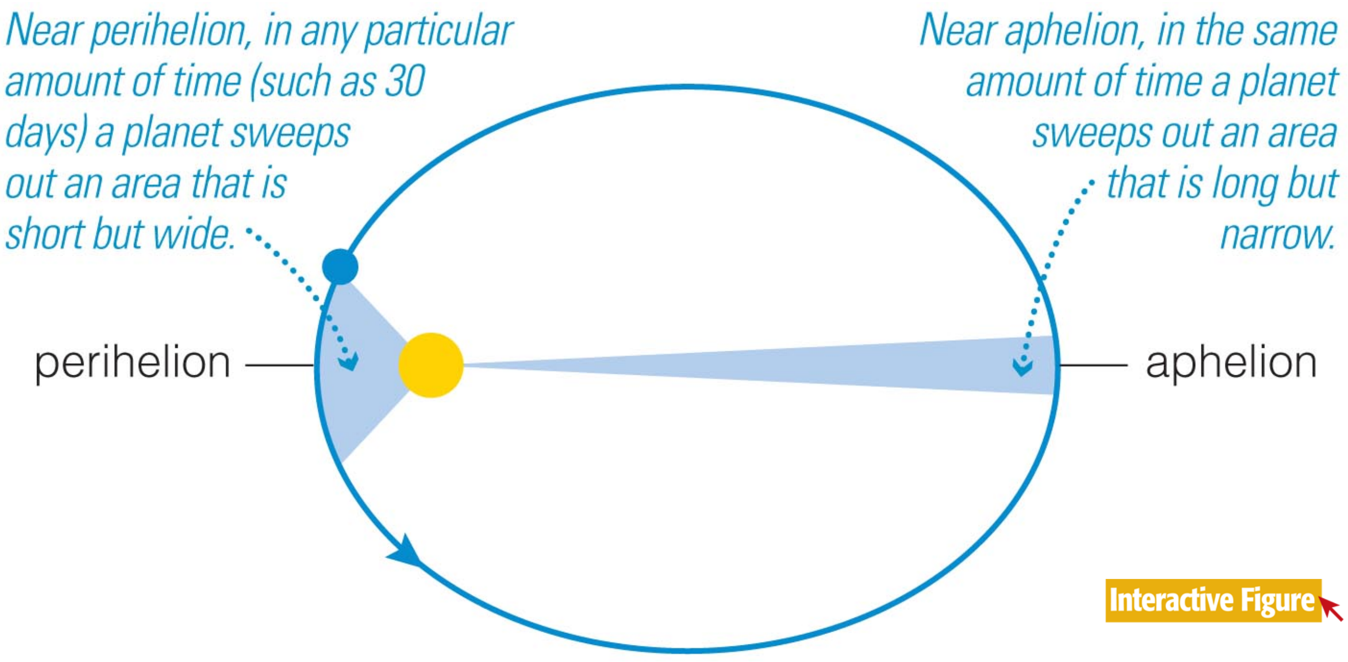
What are Kepler's three laws of planetary motion?

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



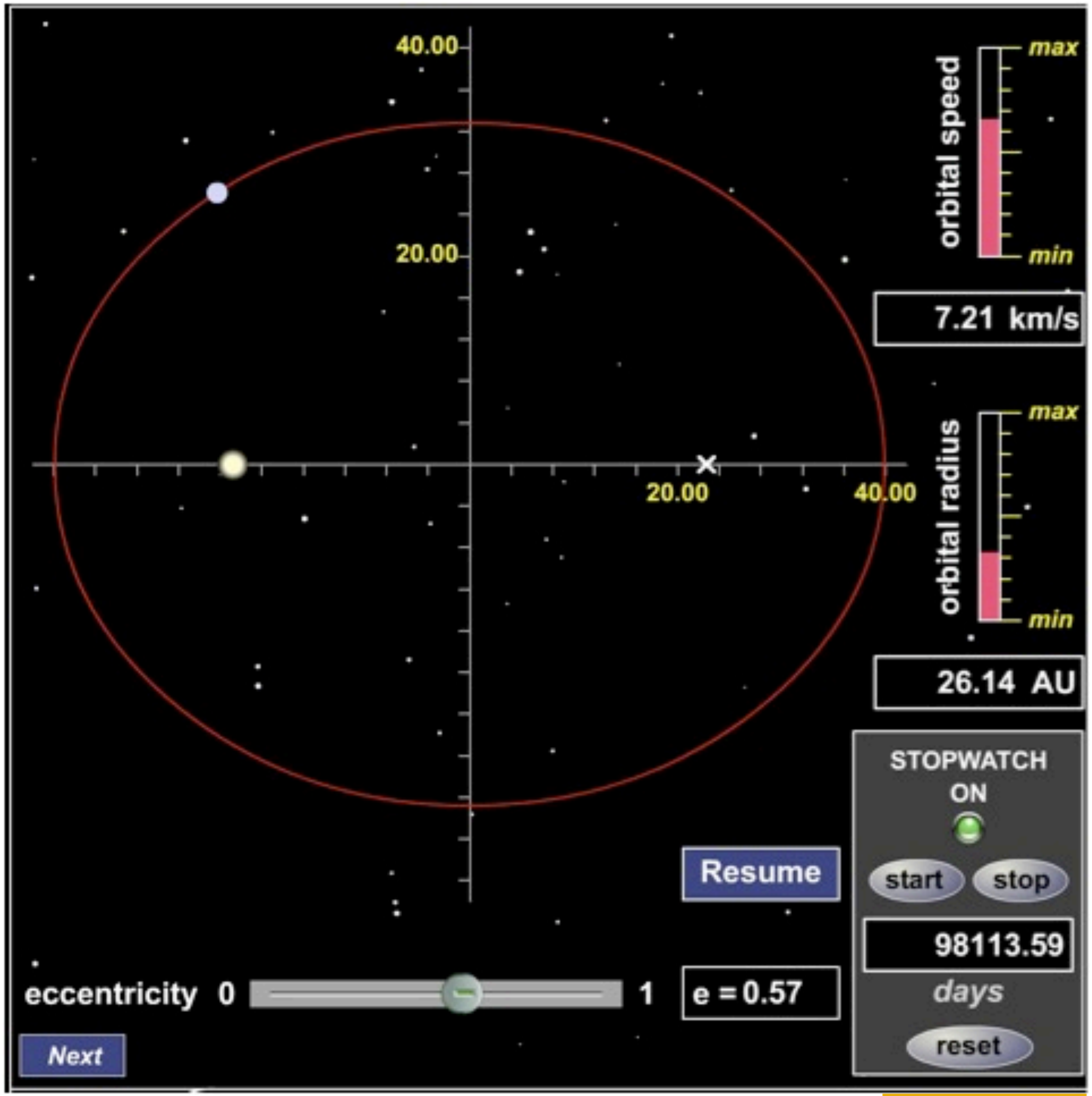
What are Kepler's three laws of planetary motion?

- **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.

What are Kepler's three laws of planetary motion?



Interactive Figure

Kepler's Third Law

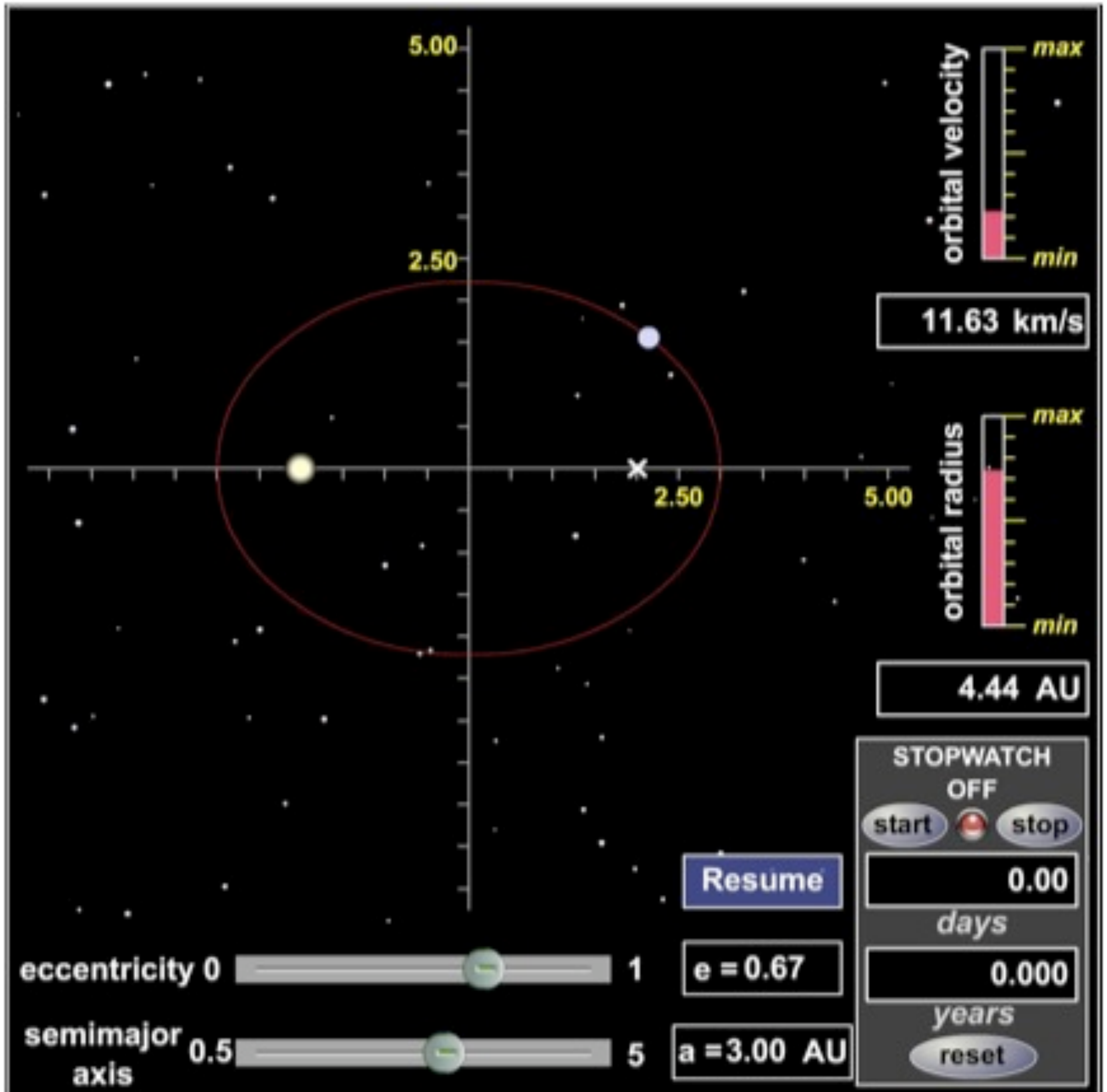
- More distant planets orbit the Sun at slower average speeds, obeying the relationship

$$p^2 = a^3$$

p = orbital period in years

a = avg. distance from Sun in AU

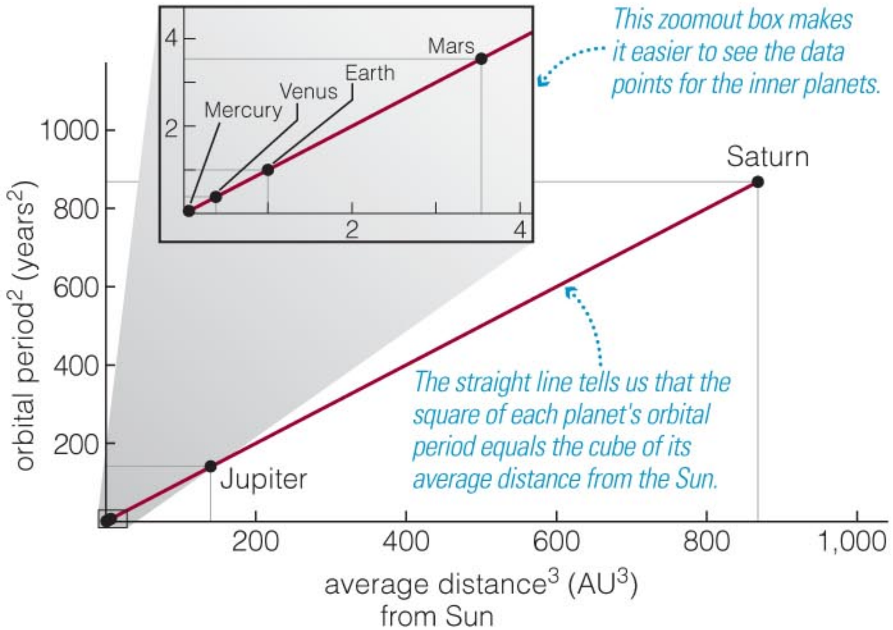
Kepler's Third Law



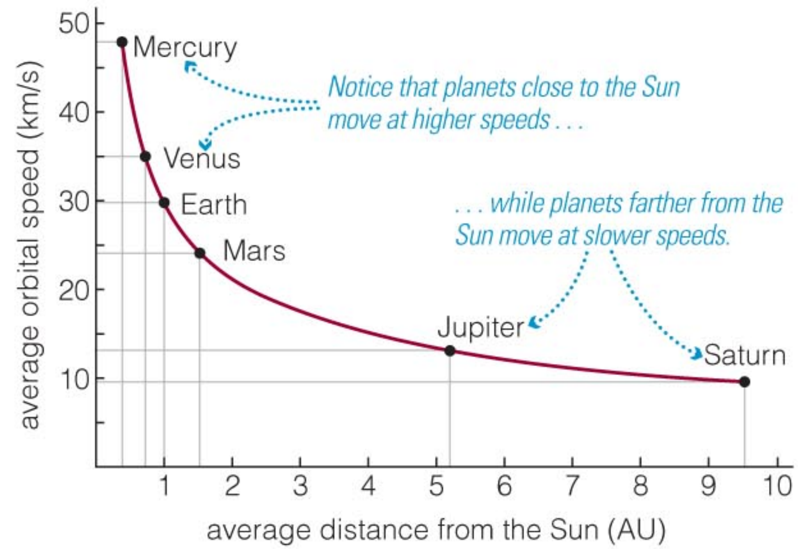
Interactive Figure

Kepler's Third Law

- Graphical version of Kepler's Third Law



a This graph shows that Kepler's third law ($p^2 = a^3$) holds true; the graph shows only the planets known in Kepler's time.



b This graph, based on Kepler's third law and modern values of planetary distances, shows that more distant planets orbit the Sun more slowly.

Clicker 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 $p^2 = a^3$

Clicker 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

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

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

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

Clicker Question

Suppose a comet had a very eccentric orbit that brought it quite close to the Sun at closest approach (perihelion) and beyond Mars when furthest from the Sun (aphelion), but with an average distance of 1 AU. How long would it take to complete an orbit and where would it spend most of its time?

A) one year, mostly beyond Earth's orbit
B) one year, mostly within Earth's orbit
C) more than one year, mostly beyond Earth's orbit
D) less than one year, mostly within Earth's orbit
E) It depends on the exact value of the eccentricity.

Clicker Question

Suppose a comet had a very eccentric orbit that brought it quite close to the Sun at closest approach (perihelion) and beyond Mars when furthest from the Sun (aphelion), but with an average distance of 1 AU. How long would it take to complete an orbit and where would it spend most of its time?

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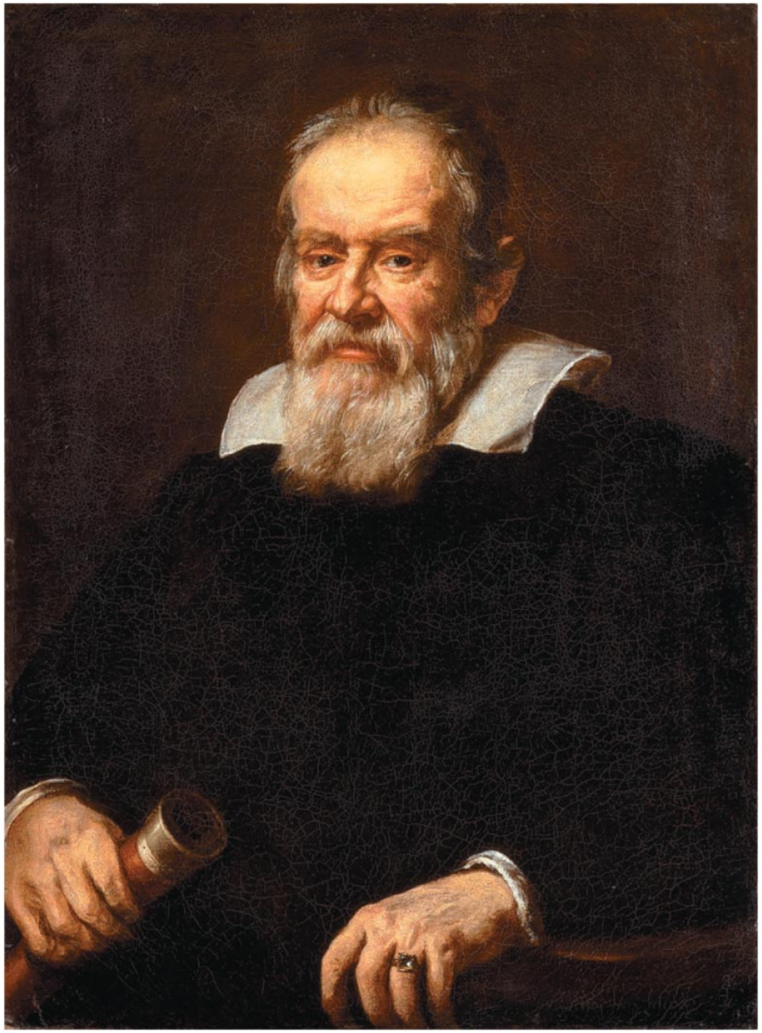
How did Galileo solidify the Copernican revolution?



Galileo (1564-1642)

Galileo overcame major objections to the 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):

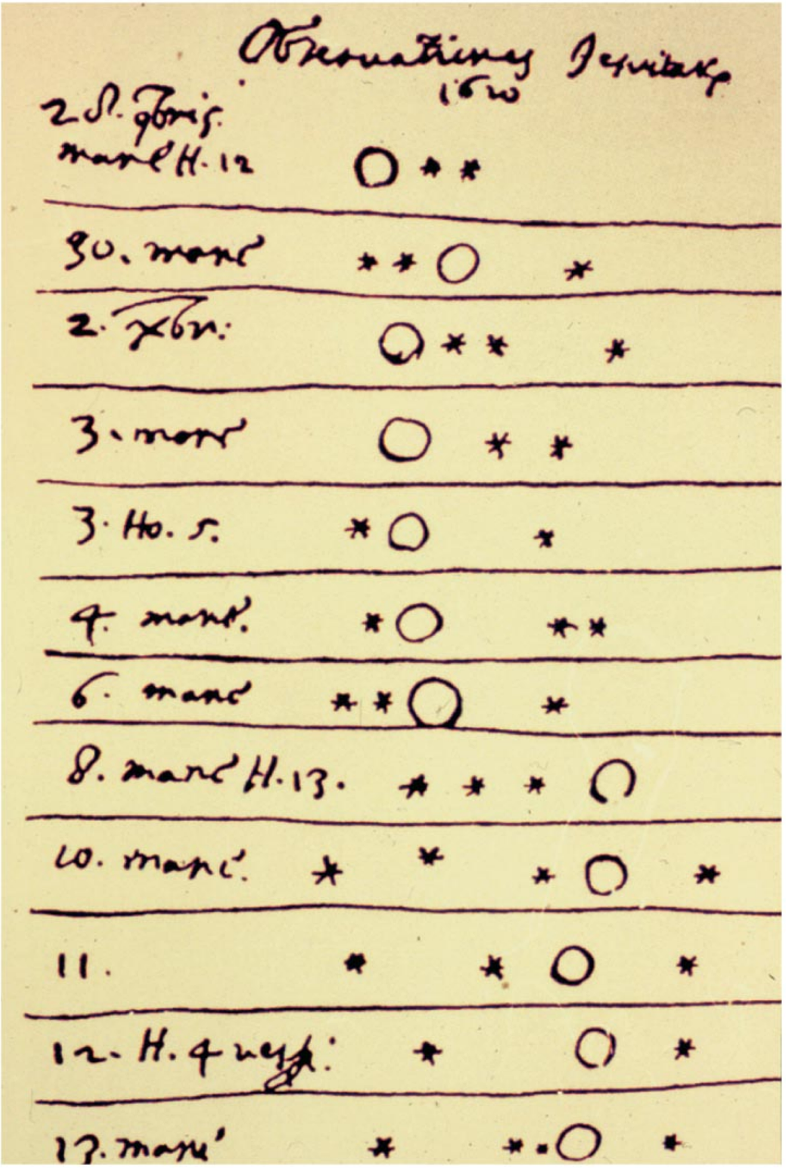
- Galileo's experiments showed that objects in air would stay with Earth as it moves.
  - Aristotle thought that all objects naturally come to rest.
  - Galileo showed that objects will stay in motion unless a force acts to slow them down (Newton's first law of motion).

Overcoming the second objection (heavenly perfection):

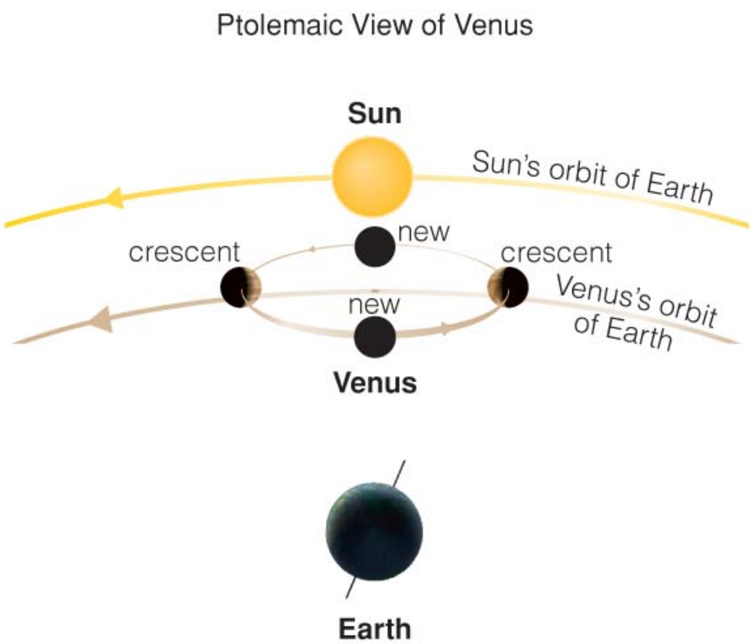
- Tycho's observations of comet and supernova already challenged this idea.
- Using his telescope, Galileo saw:
  - Sunspots on Sun ("imperfections")
  - Mountains and valleys on the Moon (proving it is not a perfect sphere)

Overcoming the third objection (parallax):

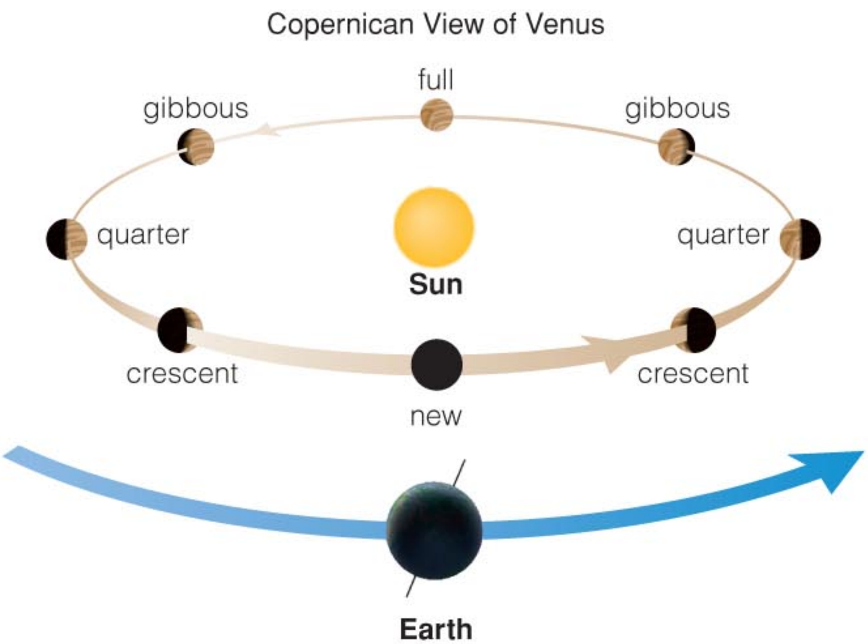
- Tycho *thought* he had measured stellar distances, so lack of parallax seemed to rule out an orbiting Earth.
- Galileo showed stars must be much farther than Tycho thought — in part by using his telescope to see the Milky Way is countless individual stars.
  - ✓ If stars were much farther away, then lack of detectable parallax was no longer so troubling.



- Galileo also saw four moons orbiting Jupiter, proving that not all objects orbit Earth
- The observations still are proving useful today, as they help us understand the evolution of orbits due to tides, which is a very slow process



a In the Ptolemaic system, Venus orbits Earth, moving around a smaller circle on its larger orbital circle; the center of the smaller circle lies on the Earth-Sun line. If this view were correct, Venus's phases would range only from new to crescent.



b In reality, Venus orbits the Sun, so from Earth we can see it in many different phases. This is just what Galileo observed, allowing him to prove that Venus orbits the Sun.

Interactive Figure

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

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 out 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 model.

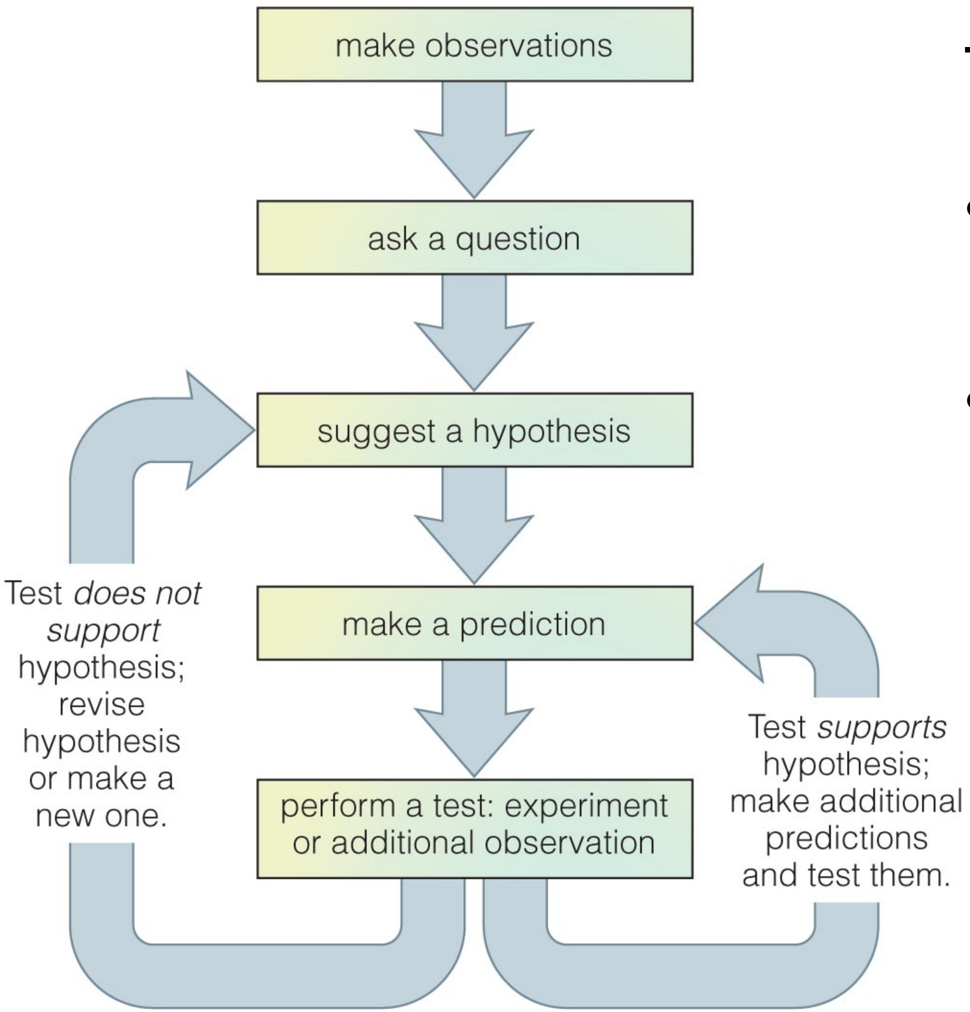
3.4 The Nature of Science

- 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.

How can we distinguish science from non-science?



<u>The idealized scientific method</u>

- 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.
    - In particular in astronomy, it is common to just do very large “surveys” and to see what we find in a particular area of the sky, or at a particular wavelength of light
  - Sometimes we follow our intuition rather than a particular line of evidence.
    - But then tests will confirm or refute your intuition

Hallmark of Science: #1

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

- (A scientific model cannot include divine intervention)

Hallmark 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")

Hallmark 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.
- Each of the competing solar system models offered predictions that were tested. Kepler's model can still be tested. In fact, slight discrepancies found at later dates led to new discoveries, such as Einstein's theories…

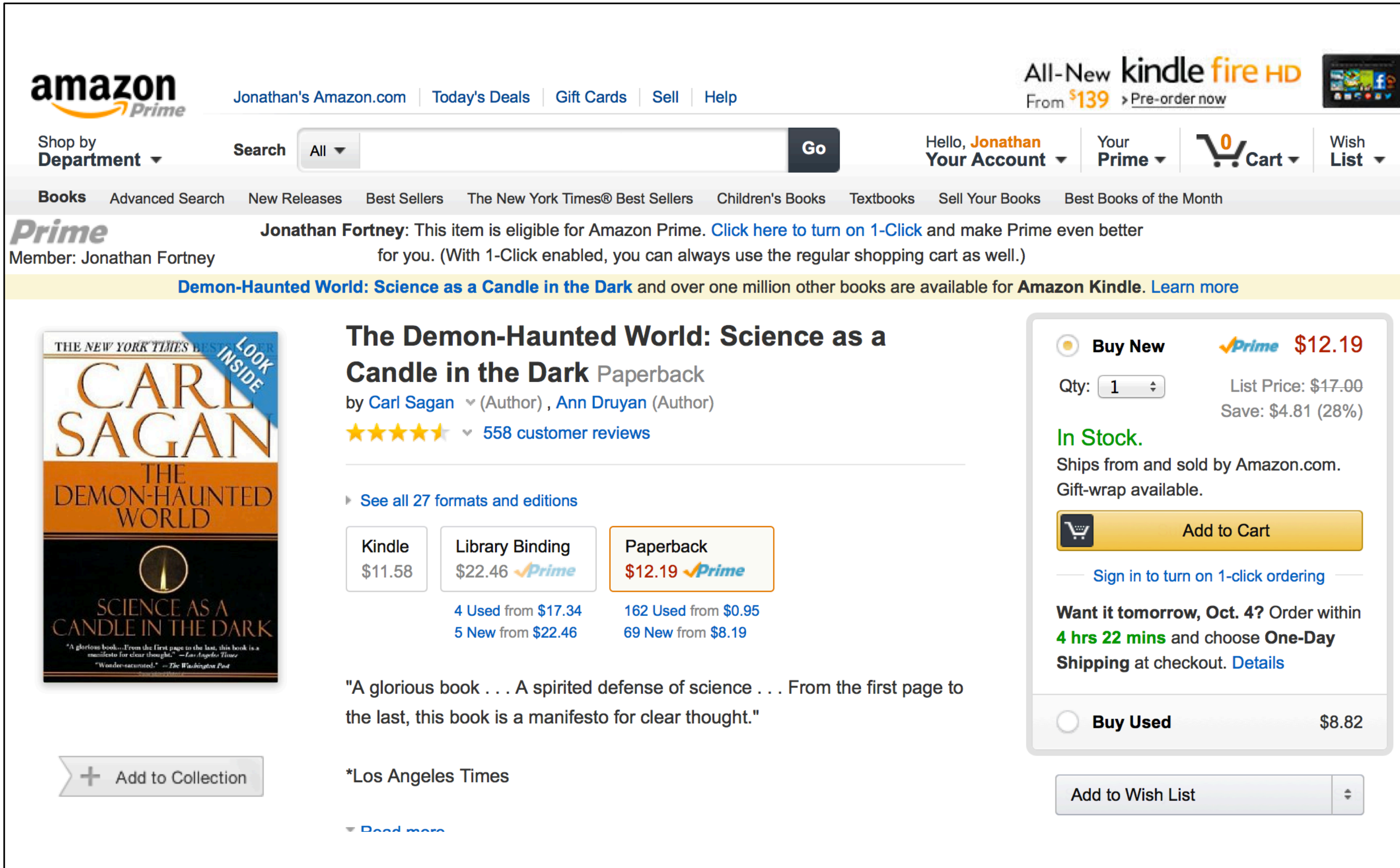
What is a scientific theory?

- 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.

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

A book that was personally very important me



3.5 Astrology

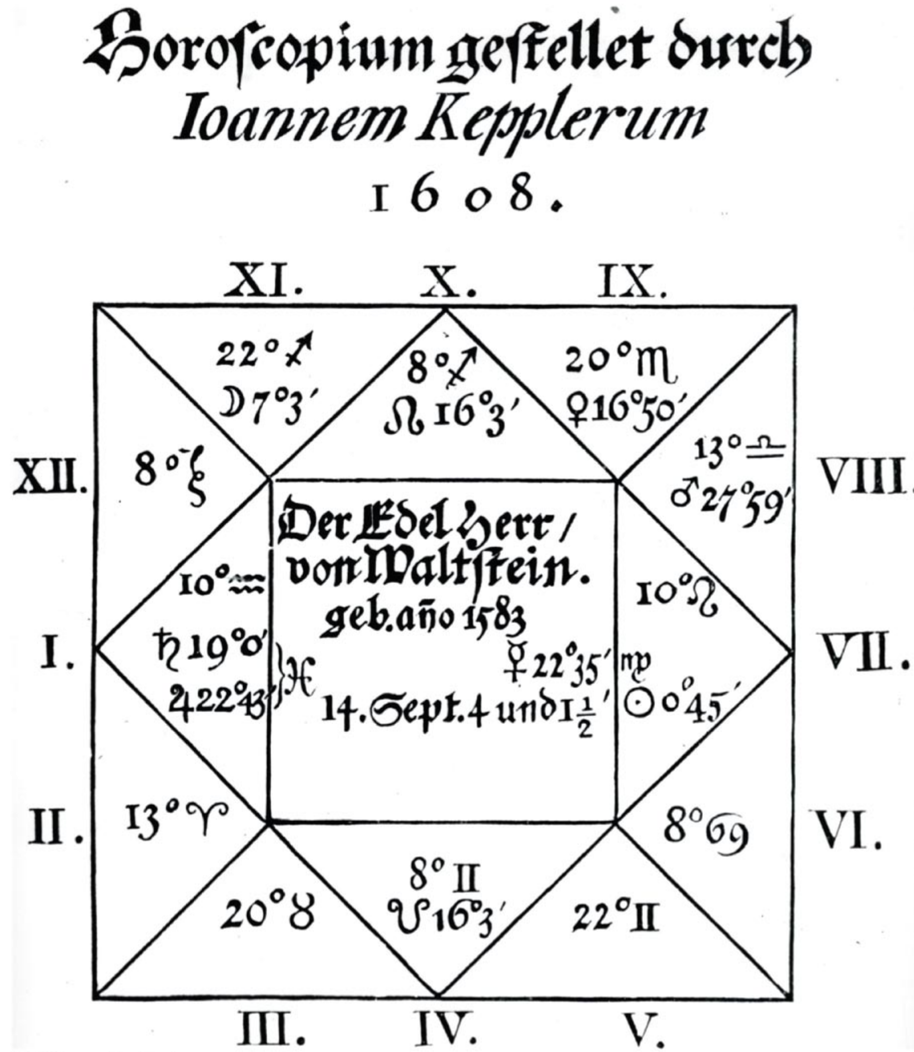
- Our goals for learning:
  - **How is astrology different from astronomy?**
  - **Does astrology have any scientific validity?**

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.



Next week

- I will be at a conference Mon-Wed
- TA Chris Mankovich will lecture on topics in Chapter 4 on Tuesday
- My office hours will be Thursday 9-11 a.m., not Wednesday
- HW #2 (covering Chapters 3 and 4) will be due on Thursday, 10/10
  - It will be up at around noon tomorrow