# Astronomy 122

This Class (Lecture 6):

Gravity and the Planets

***Homework #2 due Fri at 11:59pm!***

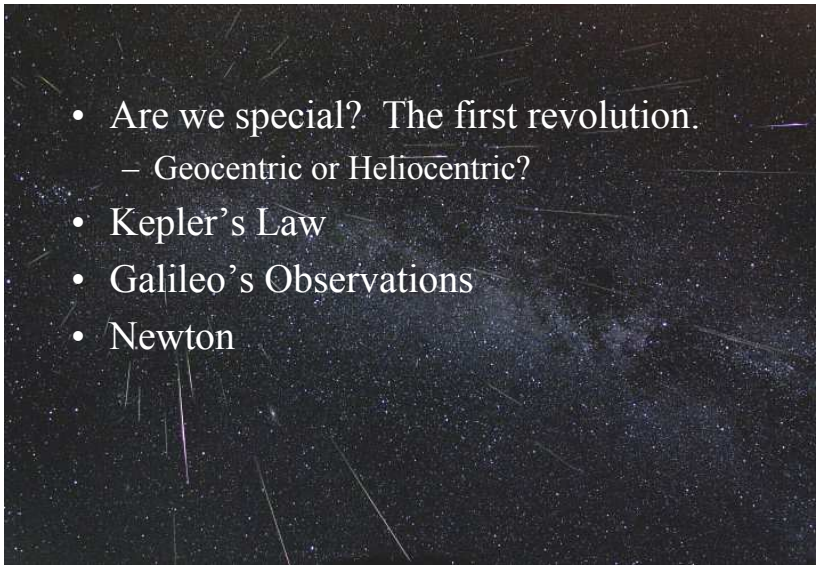
Next Class:

Matter and Light

Music: Vincent – Don Mclean



# Outline

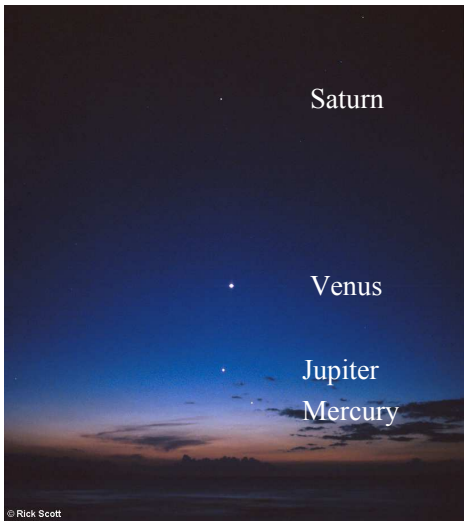


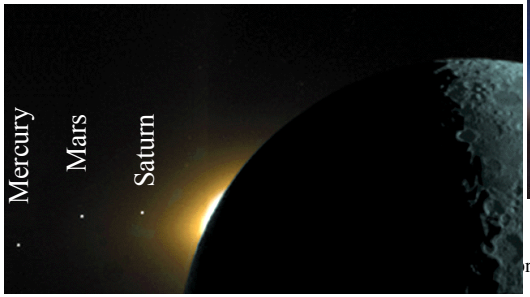
- Are we special? The first revolution.
  - Geocentric or Heliocentric?
- Kepler's Law
- Galileo's Observations
- Newton



# The Planets

- In ancient times, people noted five bright "stars" that moved through the constellations of the Zodiac over time
- These "stars" were called *planets*, from Greek for "wanderers"



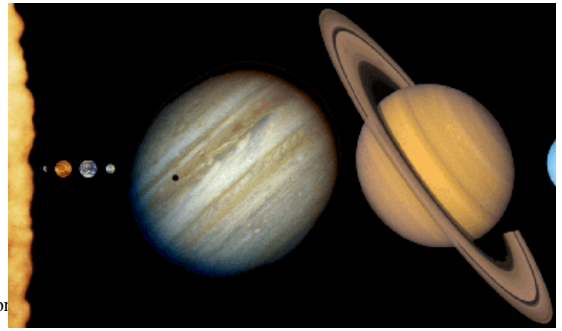






http://antwrp.gsfc.nasa.gov/apod/ap990325.html
http://antwrp.gsfc.nasa.gov/apod/ap001014.html

# Names of the Planets

- Planets were given the names of Roman/Greek gods
  - Mercury (Hermes) – Messenger God (fast!)
  - Venus (Aphrodite) – Goddess of Beauty (brilliant!)
  - Mars (Ares) – God of War (red!)
  - Jupiter (Zeus) – King of the Gods
  - Saturn (Cronus)
    - Father of Zeus



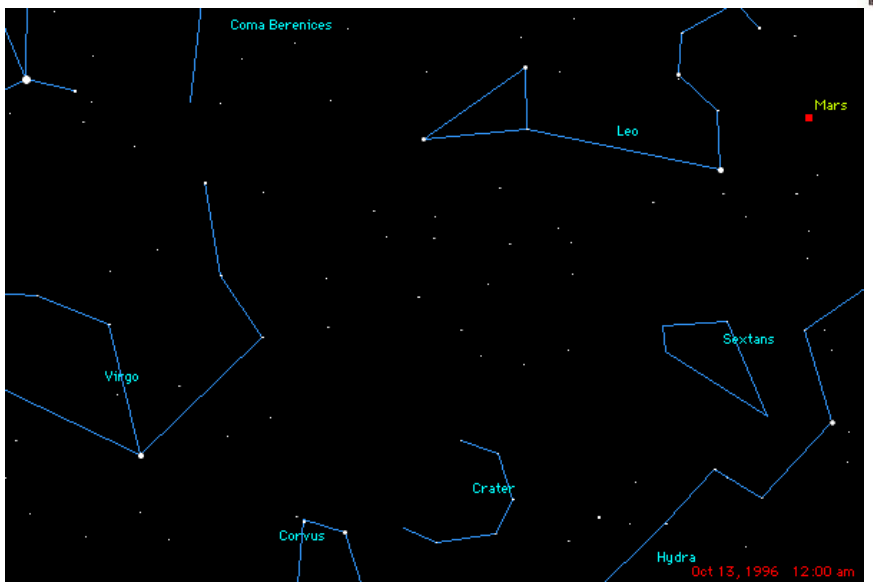
# Planetary Motion

- On a single night, planets will rise with stars and move from east to west.
- This is due to the diurnal motion of the Earth's rotation.
- However, over time, how does planet motion map on the sky?



# Mars Moves

E A S T

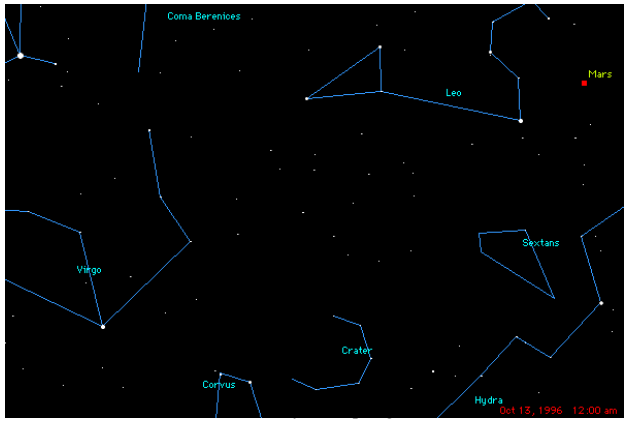



W E S T



# Planetary Motion

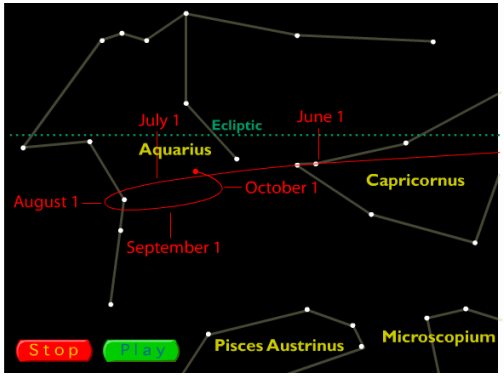
- Over many nights, planets can be seen to move west to east with respect to the stars
  - Also called ***prograde*** motion





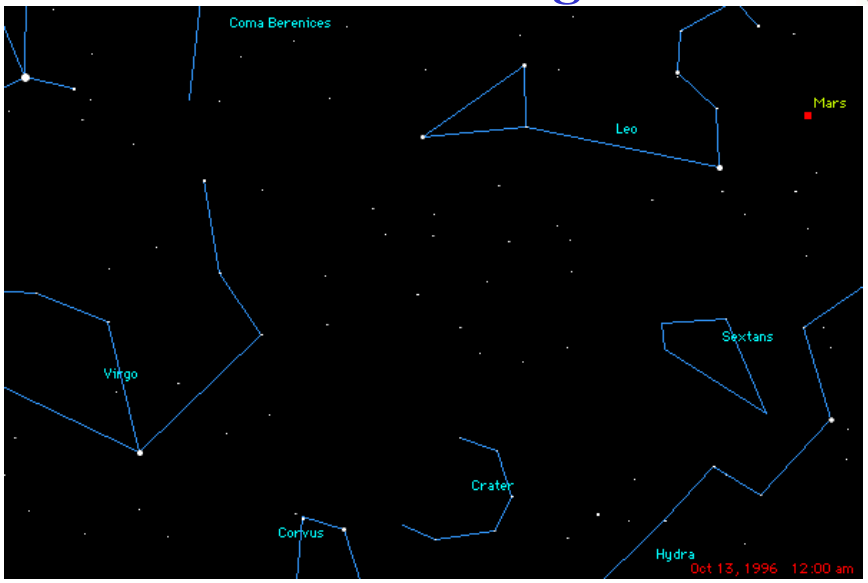

# Retrograde Motion

- Occasionally, a planet's motion (not just Mars) with respect to the stars appears to stop and reverse direction
  - Called ***retrograde motion*** (east to west)




  - Lasts for several weeks to a few months
  - Remember, this motion is much slower than the diurnal "rise in the east set in the west" motion

# Let's see that again



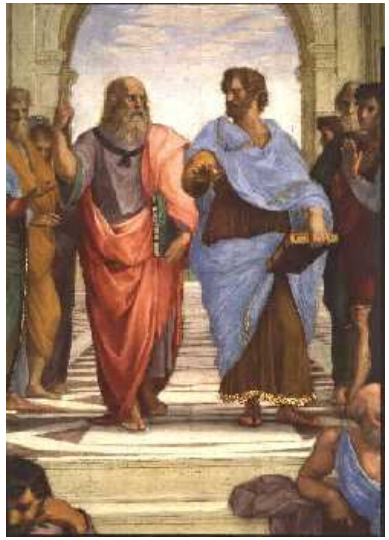

EAST

WEST



# What did the Greeks think of the Planetary Data?

- The Greeks were excellent astronomers
  - Catalogued star positions, brightness
  - Systematic, quantitative observations
- They observed that the stars, Sun, and planets appeared to revolve around the Earth.
- This is the obvious answer!





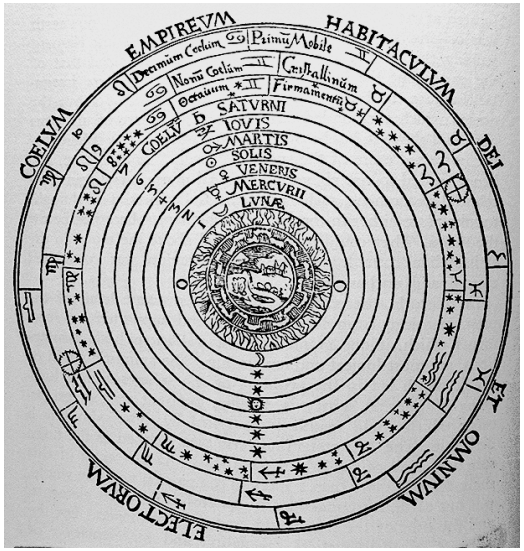
# Explaining Planetary Motion

- The Greek philosophers believed that we lived in a ***geocentric*** (Earth - centered) system
  - The heavens move in perfect circles
  - The celestial sphere is pure and unchanging
- A ***heliocentric*** (Sun - centered) model had been introduced around 280 BC by Aristrarchus, but was rejected
  - The Earth *must* be too heavy to move



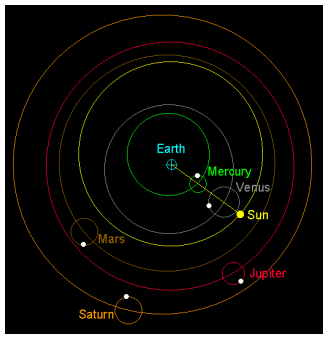
# The Geocentric Model

- The basic geocentric model is quite simple
- But how do you explain retrograde motion and the inferior planets (Mercury & Venus)?



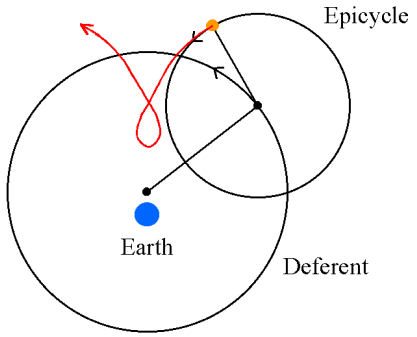
# Ptolemy (140 AD)

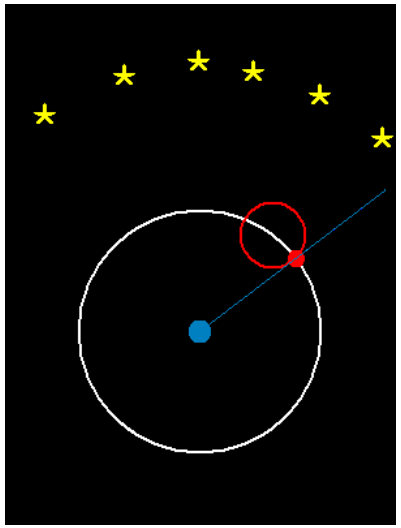
- Created a geocentric model with uniform circular motion that explained retrograde motion and inferior planets
- The Ptolemaic system






# Ptolemy Explains Retrograde Motion

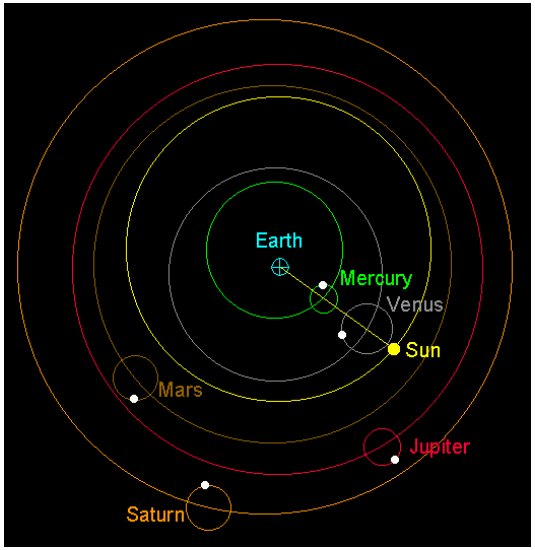




# Ptolemy Explains the Inferior Planets

- Venus' and Mercury's orbits are locked to the Sun
- Ptolemy's model becomes very complex
- Remember *Occam's Razor*…






# Is It A Theory?

- ***Yes!*** …and a reasonably accurate for its time
  - ***Data:*** Sun/moon/planet motions
  - ***Tentative Model:*** circular orbits
  - ***Prediction:*** uniform motion on sky
  - ***New data:*** retrograde motion, inferior planets
  - ***Refined model:*** epicycles, Venus & Mercury locked to the Sun
- **Result:** Ptolemaic system (theory)
  - *strength:* reasonably accurate fit of data
  - *weakness:* complex, predictions for new data?

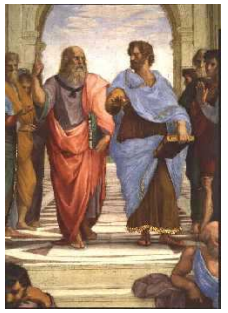
# Ptolemaic Problems

- There was no universal rule governing planetary motion
  - Just mathematical constructs to fit the data
  - No reason **why**
- Nonetheless, for a 1000 years this model ruled western astronomical thought
- By the late middle-ages, a search began for a system with simpler underlying principles
  - Ptolemy's system too complex
  - Predictions only accurate for a century or so



# Lessons: Were the Greeks Stupid?

- Not at all!
  Developed sophisticated, successful model
- But built in prejudices about the world
  not just geocentric but egocentric



What about scientists today?
Still can fool ourselves! (And have!)
But: *scientific method* is tool:

- To keep from fooling yourself
- To correct yourself when you have

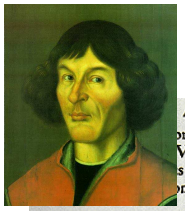
My guess:

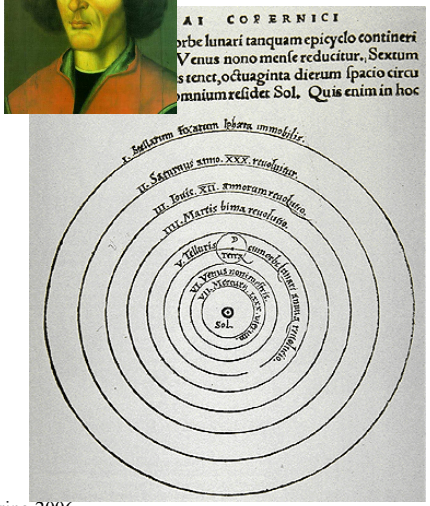
**80%** of the material in this course will stand the test of time

- Compare baseball: 30% success good
- but also: 20% of course is wrong/incomplete!
  - Which 20%? Don't know! Would fix it if we knew! So…
  - You have to learn all of it!

# Nicholas Copernicus (ca. 1540)

- Resurrected the heliocentric model
- This was dangerous
  - The geocentric system had become dogma
- Copernicus did not publish his work until the year he died.
- Still held onto the idea of perfect circular motion

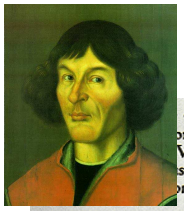






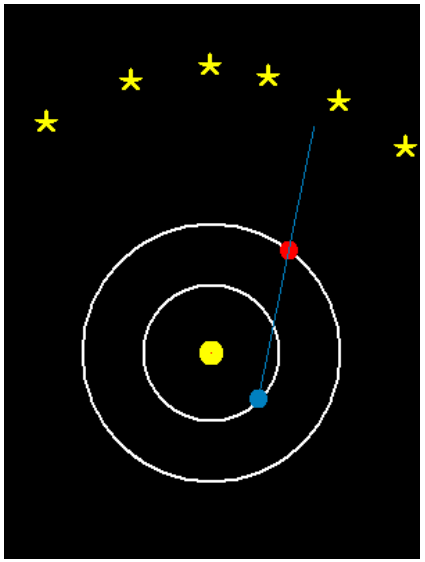

# Nicholas Copernicus (ca. 1540)

- Data problems:
  - Earth doesn't feel like it's moving.
  - Can something so heavy move so fast?
  - Wouldn't we get flung off?
  - The stars have no measurable movement.



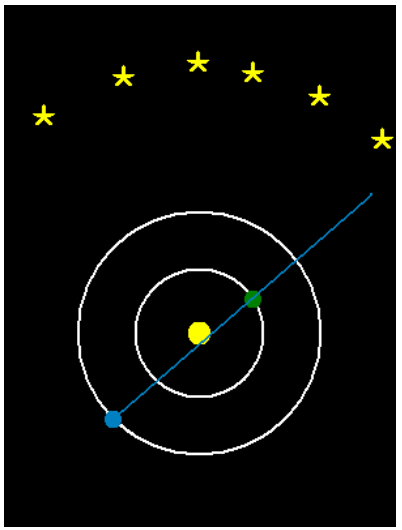
# Copernicus Explains Retrograde Motion

- Inner planets move faster than outer planets
- Retrograde motion occurs when Earth overtakes and passes (or is passed by) another planet.
- Retrograde motion is a natural consequence of planetary motions



# Copernicus Explains Inferior Planets

- Inferior planets have orbits closer to the Sun than the Earth.
- Always appear close to the Sun as seen from Earth.



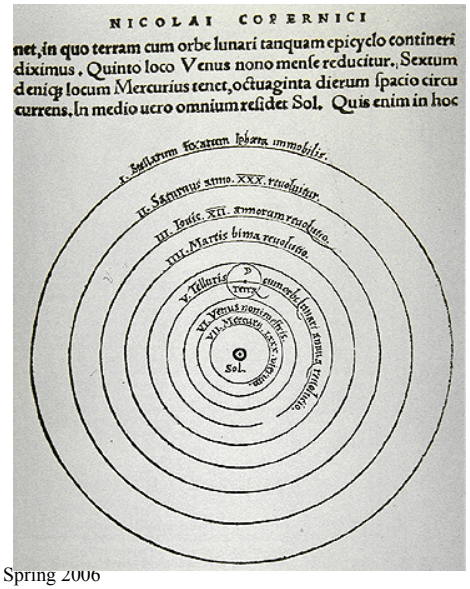


# Copernicus (1540) Heliocentric Model

BUT, keep in mind that the geocentric model was still valid at the time. Both models explained the observed motion.

Heliocentric is NOT obvious!

IT was determined a philosophical argument for 50 years! New observations were required to determine which is correct.






# Copernican Problems

- Clung to the idea of perfect circles.
  - Still needed epicycles to explain irregularities in planetary motion.
- Both Copernican and Ptolemaic models explained the observed planetary motions.
  - The Copernican model gave a simpler explanation of retrograde motion and inferior planets.
  - But, mathematically, Copernican model gave *worse* predictions of planet positions!

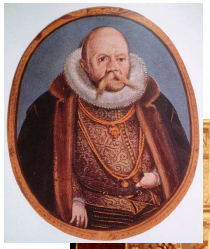
# Significance

- Despite the problems with Copernicus' model, it marked a turning point in the history of science
- It began a major philosophical shift in the culture of science
  - We are not at the center of the Universe!
  - Earth obeys the same rules as the rest of the Universe



# Tycho Brahe (ca. 1580)

- Carefully observed stars and planets using a "state-of-the-art" observatory
  - Uraniborg – "Castle of the Heavens"
- Accurate to about 1 arcminute (1/15$^{th}$ the size of the moon)
  - ***No telescopes!***

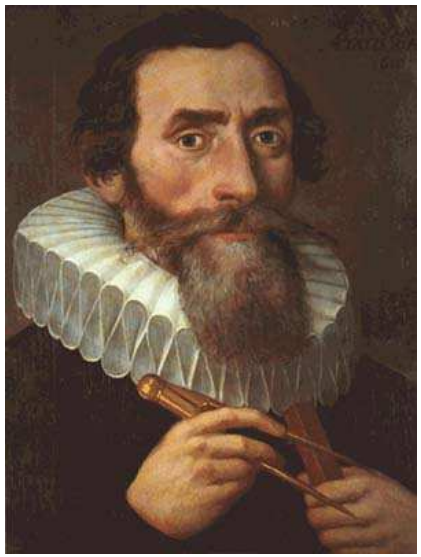




# Johannes Kepler (ca. 1600)

*"It was as if I awoke from sleep and saw a new light"*

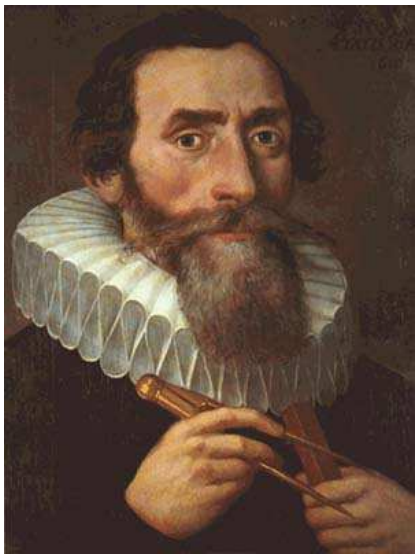
-- Kepler, New Astronomy



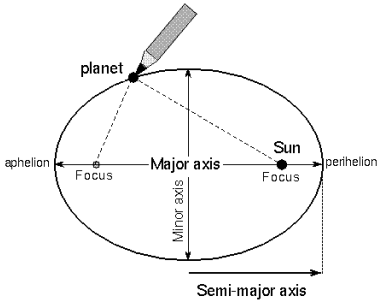


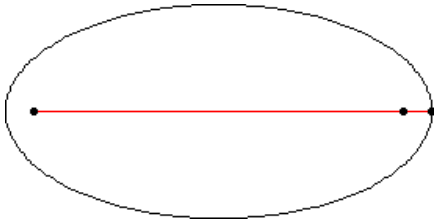
# Johannes Kepler (ca. 1600)

- Inherited a set of very accurate observations of the planets when Brahe (his boss) died
- Used the data to guide the creation of a new heliocentric theory
- Data could not be fit by circular orbits
- Considered an *ellipse*



# Kepler's First Law



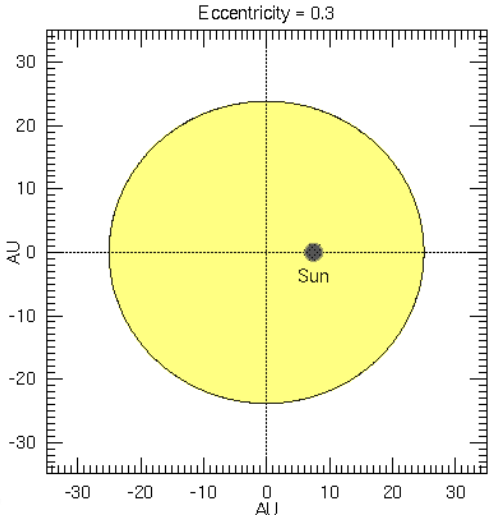
The orbits of the planets are ellipses with the Sun at one focus.

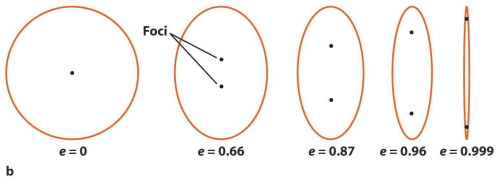
**The heavens do not move in perfect circles!**



# Orbits of planets are ellipses with the Sun at one focus

New Twist– even the Sun isn't at the center of the solar system now. How does that change our view of the Universe and our place in it?

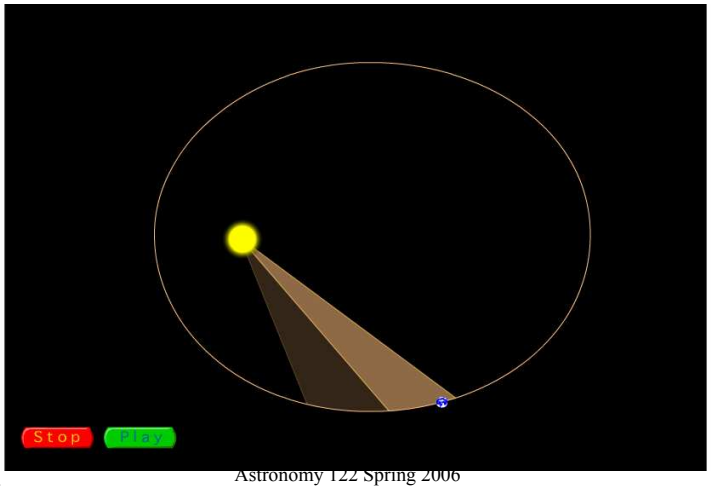





# Kepler's Second Law

The line that connects the planet to the Sun sweeps out equal areas in equal time



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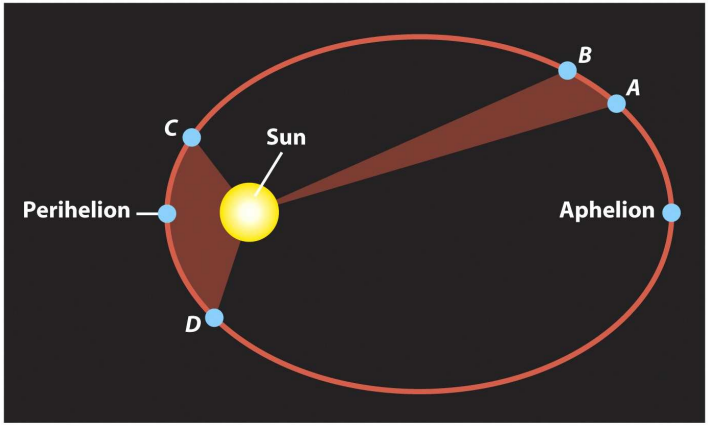


# Inequality of the Seasons

- Planets move faster when closer to the Sun
  - Fastest at perihelion (closest to the Sun)
  - Slowest at aphelion (farthest from the Sun)
- Effect witnessed as the *inequality of the seasons*
  - Northern spring & summer have 93 days
  - Northern autumn has 90 days
  - Northern winter has 89 days
  - Why? Perihelion is on Jan 5th, Earth moves fastest in its orbit during our winter



# Sidetrack: Meter Stick

- Average Distance from Earth to the Sun = $1.5 \times 10^8$ km (or 93 million miles).
- Too lazy for all that…
- So, astronomers defined a new unit
  - Average distance from Earth to the Sun = 1 Astronomical Unit (AU)
  - Useful for measuring distances in the Solar System




# Kepler's Third Law

A planet's orbital period (P) in years, squared, equals the semimajor axis of its orbit (a) in AUs, cubed

$$P^2 = a^3$$

**years** **AUs**

**(astronomical units)**



# Question

Consider two planets, A and B, orbiting a distant star. Planet B orbits twice as far from the star as planet A does. How does planet B's orbital period compare to planet A's?

a. half as long

b. the same

c. twice as long

d. more than twice as long

# Planetary Orbits

- The farther away from the Sun, the longer it takes for the planet to orbit AND the slower it's average orbital speed

| Planet | P (yr) | a (AU) | $P^2$ | $a^3$ |
|---|---|---|---|---|
| Mercury | 0.24 | 0.39 | 0.06 | 0.06 |
| Venus | 0.61 | 0.72 | 0.37 | 0.37 |
| Earth | 1.00 | 1.00 | 1.00 | 1.00 |
| Mars | 1.88 | 1.52 | 3.5 | 3.5 |
| Jupiter | 11.86 | 5.20 | 141 | 141 |
| Saturn | 29.46 | 9.54 | 868 | 868 |

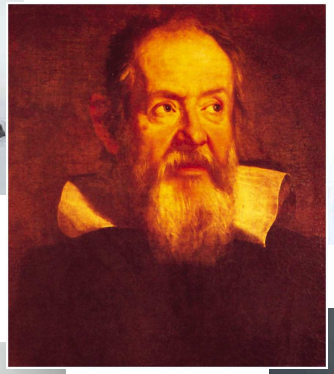


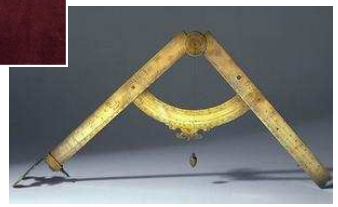
# Java Fun with Kepler

http://csep10.phys.utk.edu/astr162/lect/binaries/visual/keplerold frame.html



# Galileo Galilei (1564-1642)



# Galileo Galilei (1564-1642)

- Mathematics chair at Pisa & Padua
- Conducted experiments in mechanics
- Invented the compass & microscope
- Improved on existing telescope designs




# Galileo the Astronomer

- The first to systematically use a telescope to observe the heavens
- And record the results of his observations!



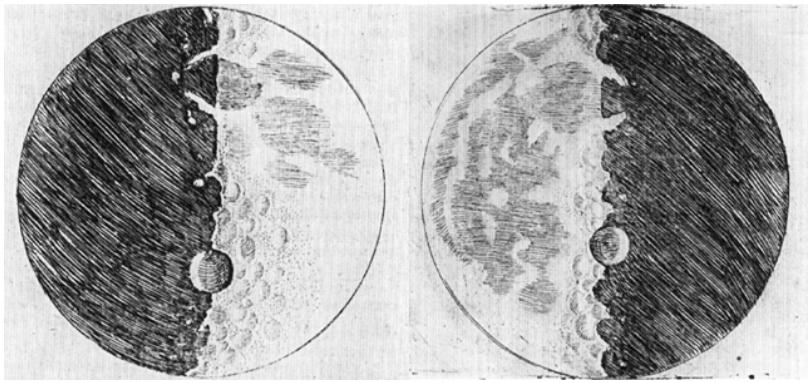
# Galileo's Discoveries in the Heavens

- Mountains and valleys on the Moon
- Sunspots
- Saturn is "elongated"
- The Milky Way consists of faint stars
- Venus shows phases, like the Moon
- Jupiter has moons




# Mountains on the Moon

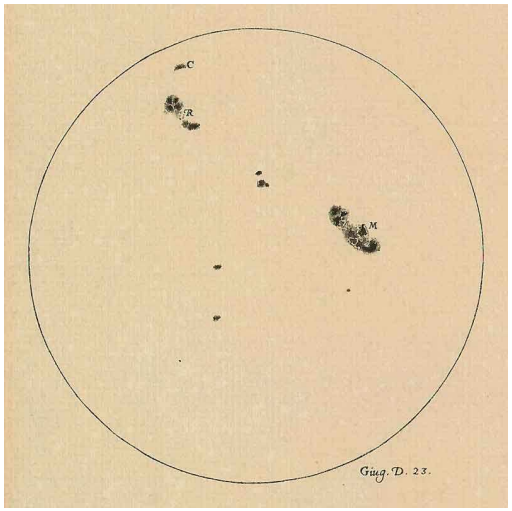
- Galileo observed mountains on the Moon.
- The Moon is **not** a perfect sphere!





# Sunspots

- Galileo projected the Sun onto a screen with his telescope
- He saw dark spots, and they moved!
- The Sun is imperfect…
- And it rotates!



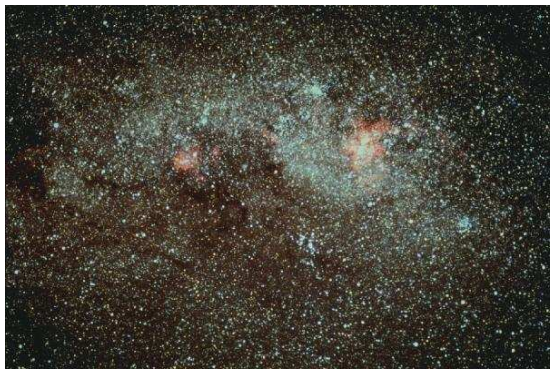
# "Elongated" Saturn

- When Galileo observed Saturn, he saw that the planet looked elongated
- Galileo described it as "composed of three"
- His telescope wasn't powerful enough to resolve the rings we see today



# The Milky Way

- "Whichever direction one chooses for the telescope, immediately a very large number of stars can be seen"

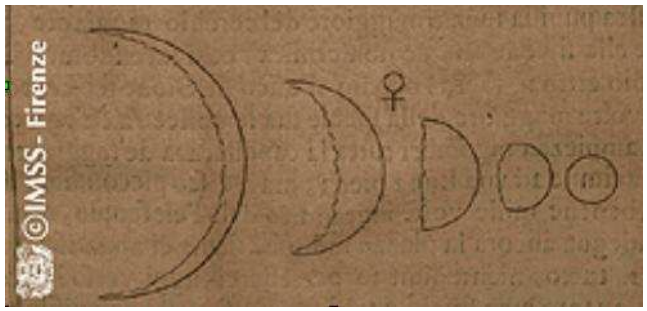


- The Milky Way is made of faint stars!



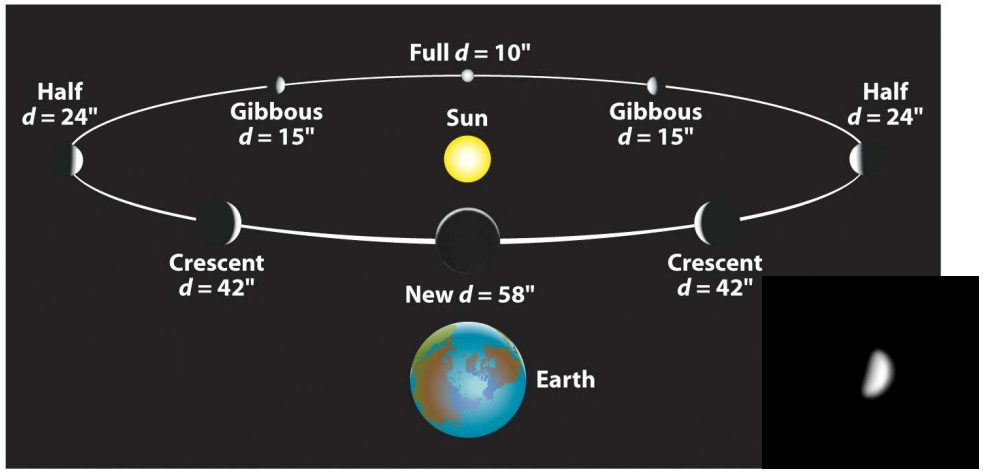
# Phases of Venus

- When Galileo looked at Venus, he saw that Venus has phases, like the Moon!
- The planets must reflect light from the Sun!
- Also, Venus changes size dramatically






# Phases of Venus




Could not be explained with the geocentric model!

http://www.calvin.edu/academic/phys/observatory/images/venus/venusb.html

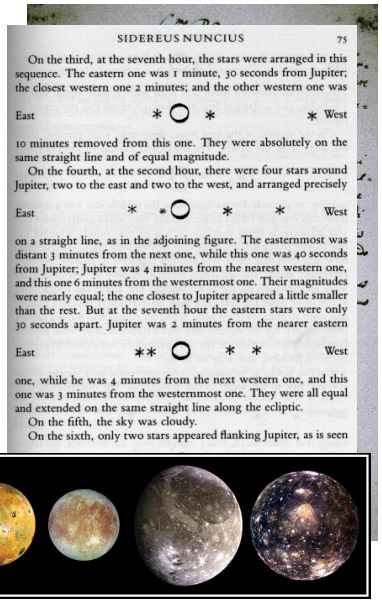
# Data: Venus

Compare the Heliocentric to Geocentric models to explain the phases of Venus.

http://www.astro.ubc.ca/~scharein/a310/SolSysEx/phases/Phases.html



# The Moons of Jupiter


SIDEREUS NUNCIUS 75

On the third, at the seventh hour, the stars were arranged in this sequence. The eastern one was 1 minute, 30 seconds from Jupiter; the closest western one 2 minutes; and the other western one was

East * ○ * * West

10 minutes removed from this one. They were absolutely on the same straight line and of equal magnitude.

On the fourth, at the second hour, there were four stars around Jupiter, two to the east and two to the west, and arranged precisely

East * * ○ * * West

on a straight line, as in the adjoining figure. The easternmost was distant 3 minutes from the next one, while this one was 40 seconds from Jupiter; Jupiter was 4 minutes from the nearest western one, and this one 6 minutes from the westernmost one. Their magnitudes were nearly equal; the one closest to Jupiter appeared a little smaller than the rest. But at the seventh hour the eastern stars were only 30 seconds apart. Jupiter was 2 minutes from the nearer eastern

East ** ○ * * West

one, while he was 4 minutes from the next western one, and this one was 3 minutes from the westernmost one. They were all equal and extended on the same straight line along the ecliptic.

On the fifth, the sky was cloudy.

On the sixth, only two stars appeared flanking Jupiter, as is seen

- Galileo found that Jupiter had 4 moons
- Orbited Jupiter, not the Earth!
- These moons are now called the Galilean Moons





# Galileo, Superstar

- Galileo's discoveries made him famous
- Everyone wanted to see the "Medicean Stars"
  - Galileo named the moons of Jupiter in honor of his financial backers
- In 1610, he was named court mathematician to the Grand Duke of Tusancy
- But…


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
unicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
QVATVOR PLANETIS
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.



# Galileo, Troublemaker

- Galileo directly challenged the geocentric view held by the authorities of the day
  - Everything does **not** orbit the Earth
  - The heavens are **not** perfect spheres
- Published *"Dialogue Concerning the Two Chief World Systems"* in 1632
  - Compared the Copernican system with the Ptolemaic system
- In 1633, Galileo was brought before the Inquisition
  - He was forced to recant his support of the Copernican system
  - Placed under house arrest until his death in 1642

# After Kepler's Laws

Kepler discovered these patterns in nature by using the data that Tycho collected, BUT the world had to wait until someone could understand the Natural Law that predicts Kepler's Laws.

The real problem: On Earth we're use to things that move but always come quickly to rest. Why don't the planets stop?

Galileo started the ball rolling here too.



# Galileo: Physicist

- Disproved Ptolemaic system
- Rome bullied him into recanting (cleared in 1992)
- Now we understand the motions and the fact that the solar system MUST be Heliocentric, but now we need a reason why?
- "Paradigm shift" – radical change in outlook/conceptual framework



# A Feather and a Hammer

http://www.hq.nasa.gov/office/pao/History/alsj/a15/a15v_1672206.mpg