Lecture 4

Astronomy:
Ancient Cosmology to Kepler and Galileo
The Copernican Revolution

Observations of the sky

Astrology
Pseudoscience

?

Astronomy
Science

Physics

Horoscopes
Fortune Telling
. . . . .

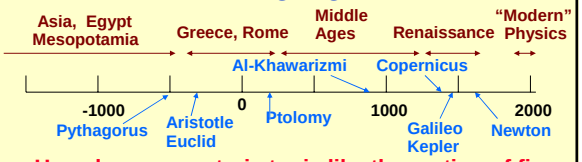
Announcements

- **Today:**
- **March Ch. 4; + additional material (Scientists in Timeline)**
  - Extra reading **(Optional)** for the interested in history of astronomy : Thomas Kuhn, "The Copernican Revolution"
- **Next Time**
  - Newton puts it all together:
    The 3 Laws
    The law of gravitation
  - Read March Ch 2-4

Today

- **What do we observe in the sky?**
- **Sun, Moon, Stars, Planets**
- **Ancient Observations - which are still useful!**
- **Ancient Cosmologies - facts or invention?**
- **Problem of the Planets (Wanderers)**
- **The strange motion of the planets has led to two competing world views**
  - **Astronomy searches for explanations in simple laws - leads to new science**
  - **Astrology treats the motion as somehow related to life on earth - leads to fortune telling, horoscopes, ….**

Timeline



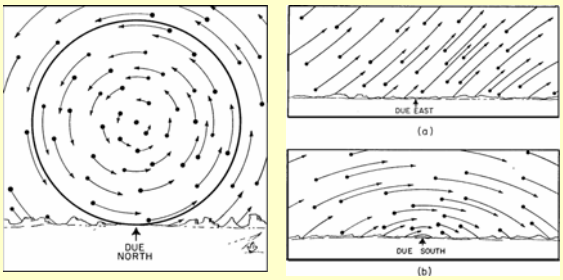
- **How does an esoteric topic like the motion of five tiny bright points in the sky lead to divergent world views?**
- **The ancient astronomers and the Renaissance giants like Copernicus, Brahe, Kepler, and Galileo made observations and analyses that determine how we think about our place in nature -- and how we apply "universal laws" to the universe!**

What are the astronomical objects that dominate our lives?

- **Sun - appears to go around the earth once per day in westerly direction - path changes in a regular way, repeating every year**
- **Moon - appears to go around the earth slightly faster than sun - so it "laps' the sun each 28 days – a lunar month**
- **Stars - "millions" all appear to go around the earth together in regular paths slightly faster than the sun – eternal, unchanging!**
- **Determines the calendar**
  - **Year -- Sun**
  - **Month -- Moon**
  - **Week -- phases of the moon**
  - **Day -- Sun**

What do we observe in the sky?

- **Sun, Moon, Stars in eternal, regular motion**
- **From a point in the Northern Hemisphere, the stars appear to move as shown:**



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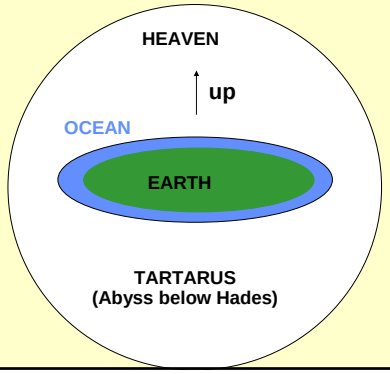
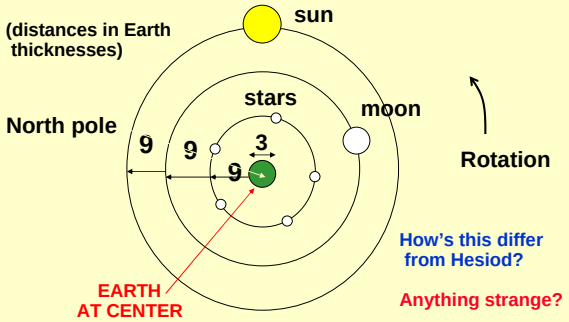
In the Beginning . . .
Ancient Cosmology: Babylon, Egypt, ...



Example of description of the cosmos) Hesiod (8th Century B.C.)

- **Physics**
  - Up and down are defined - sets the order of things Conclusion: space not the same in all directions.
  - Earth is at center.
- **Meaning**
  - Each component is important to people
  - The explanation is purely poetic and emotional
- **Methods**
  - No supporting evidence for the two conclusions above
  - No TESTABLE implications mentioned

Anaximander (6th century BC)



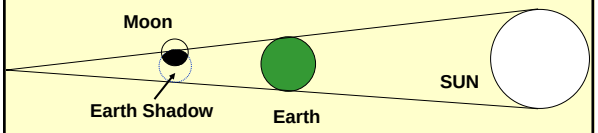
Spheres turning, Hot on Outside, Cold on Inside

Classical Greece
Pythagorus and followers
(5th Century B.C.)

- Great advances in mathematics – especially geometry
- Systematic Arguments for a Spherical Earth and other bodies - moon, sun
- "Higher" Principle: A Sphere is the most perfect shape possible -- the most symmetric
- Observation: See next slides

What observations indicate that the earth is spherical?

- In a lunar eclipse, the shadow of the earth on the moon is like that of a sphere



Appearance of Moon during lunar eclipse

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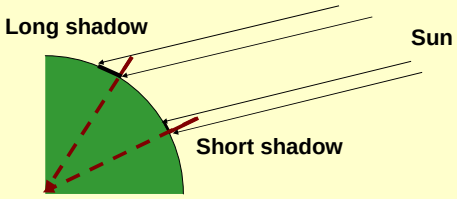
Classical Greece
4th - 3rd Century B.C.
(Aristotle lived 384-322 B.C.)

- Determined the radius of the earth! (Eratosthenes)
- The distance to the moon and sun! (Hipparchus and Aristarchus)
- How did they do that ???

Measuring the earth
Eratosthenes, 4th Cent. BC

Librarian of the great library at Alexandria



- Shadows depend upon
- North-South Location

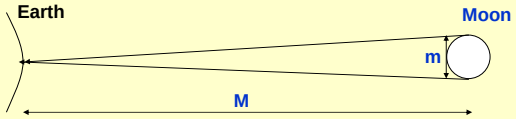
Similarly, position of stars depend upon location

How Good Was the Measurement of Eratosthenes?

- On a day when the sun was directly overhead at Syene (far southern Egypt)
- The angle at Alexandria (5000 stadia north) was 7.2 degrees, 1/50 of a full circle
- So the circumference of the earth must be 50 x 5000 stadia = 250,000 stadia
- Roughly 5% less than today's accepted value! around 24,000 miles, 40,000 km
  - (Radius = Circumference /2 π)

Observations that give important clues

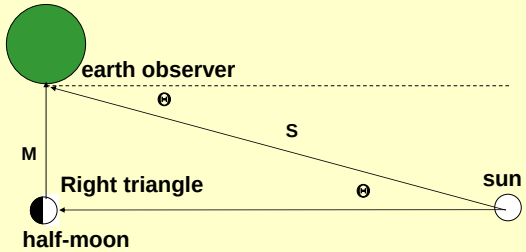
- (Note: All the equalities given in the following are approximate!)



(Homework)

- The apparent angle of the moon gives M/m = 120
- The apparent angle of the sun also gives S/s = 120
- How can you show that the sun is much farther than the moon? (S >> M)?

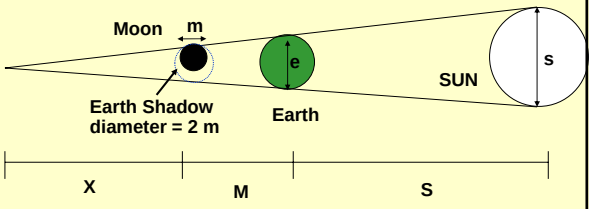
How can you show that the sun is much farther than the moon? (S>>M)



- Aristarchus (250 BC) found Θ ~ 3 degrees, or about 1/100 of a full circle
- So M/S = 2π / 100 or S/M = 100/ 2π or S is about 20M.
- But we still do not know M or S !

How large is the Moon? How Far?

- (also due to Aristarchus)
- In a lunar eclipse, the time the moon is in the shadow of the earth depends on the moon's size & distance.
- Observation: At the moon the earth's shadow is very nearly twice the diameter of the moon



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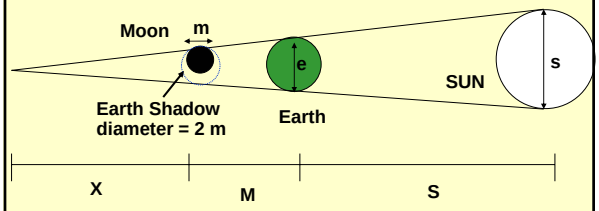
Aristarchus' Calculation and results



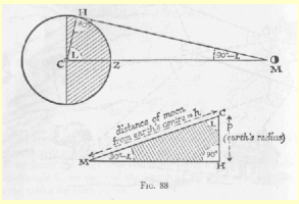
- We already know S/s = M/m with S >> M
- New observation: $\frac{X}{2m} = \frac{X+M}{e} = \frac{X+M+S}{s} \sim \frac{S}{s} = \frac{M}{m}$
- Red equations ⟶ X = 2M
- Finally $\frac{2M}{2m} = \frac{3M}{e}$ ⟶ $m = \frac{e}{3}$

Aristarchus' Conclusions

- Diameter of Moon = 1/3 Diameter of Earth
- Modern result: closer to 1/4
- Truly an achievement in 3rd Century B. C. !
- Also Aristarchus found s = 20 m, so s = 7e
- So sun's VOLUME is 7 x 7 x 7= 350 times Earth's!
- Not bad, but Sun is really much farther and much bigger (s=110 e).
- How many Earth's would fit in Sun?
- Is this little Earth the center of the Universe?

Measurement of distance to Moon

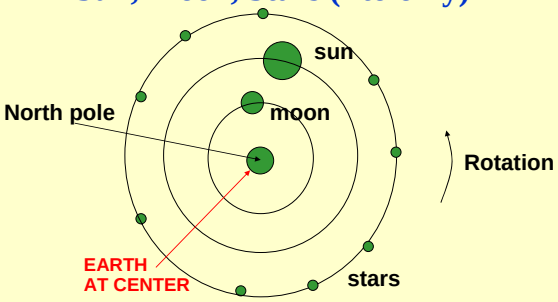
- Hipparchus (Homework)



Summary of the Advanced Astronomy of Classical Greece

- Science of Classical Greece 5th - 3rd Centuries B.C.
  - Among many achievements:
    - Spherical Earth
    - Celestial Sphere of stars
    - Description of motion of sun, moon
  - Actual measurements of the sizes & distances of the earth, moon & sun
- Culmination in the work of Aristotle (384 - 322 B.C.) and others ---- and finally Ptolomy (150 AD)

Earth Centered Model of Sun, Moon, Stars (Ptolomy)



What is the evidence for and against?
A step backward?

Exercise

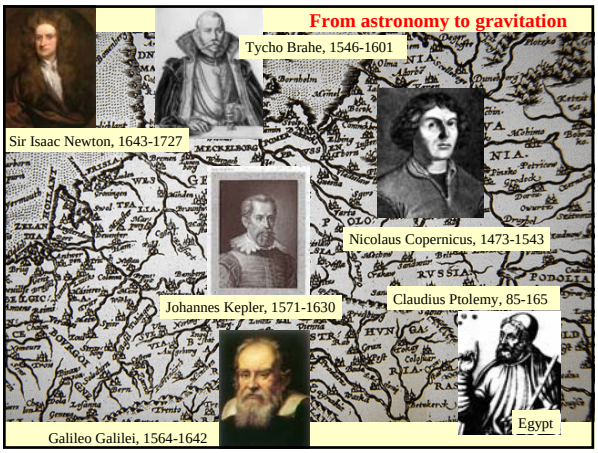
- We now "know" that
  1. The earth rotates on its axis
  2. The earth revolves about the sun
  3. The moon revolves about the earth
- How do we "know" ?
- Can one prove just from observations on the earth that:
- The earth revolves about the sun?

But yet:
- The moon revolves about the earth?

Lecture 4

The Copernican Revolution

- Science Proceeds in great revolutions
  - Actual measurements on minute details
    - Motion of the 5 planets
    - Observation over thousands of years
  - Proposal of conceptual models
    - Drawing conclusions that are TESTABLE by experiments
  - Bold conclusions leading to general principles
- Occurred in the renaissance
- Greatly aided by the printing press and technological inventions

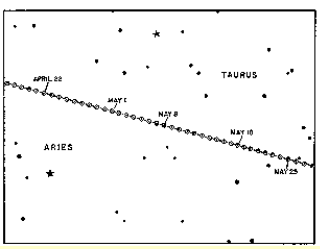


Problem of the Planets

- The model of the universe as the sun, moon, and a sphere containing the stars explains motion of "millions & millions" of stars. But fails for five points of light, the wanderers: Mercury, Venus, Mars, Jupiter & Saturn.
- The main motion is similar to the sun moving westward with the stars, but slightly slower. Relative to the stars, they move eastward along the "Zodiac".
- These are the "anomalies" that ultimately led to a revolution in our understanding of the universe.

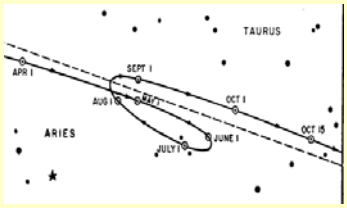
Motion of Sun, Moon, Planets along the "Zodiac"

- Sun moves through the constellations
- Observe directly by the position of the stars at sunrise and sunset



Problem of the Planets

- The motion of each planet - Mercury, Venus, Mars, Jupiter & Saturn - follows a different path at a different speed along the "Zodiac"
- Their speed varies and sometimes they move backward!



What is the importance for humans?

Problem of the Planets

- The motion of each planet - Mercury, Venus, Mars, Jupiter & Saturn - follows a different path at a different speed along the "Zodiac"
- Their speed varies and sometimes they move backward!

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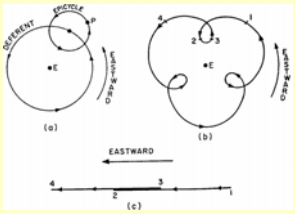
Solutions??

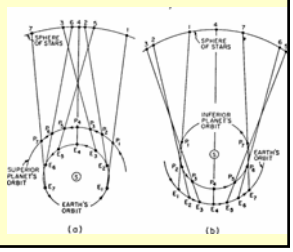
- **Ptolemy (150AD):**

Planets move on circles (epicycles) centered on another circle (deferent) which moves uniformly around the Earth.



- **Aristarchus (c 250 BC)**
  Copernicus (1473-1543)

Sun is the center of the universe. All planets (including Earth) move about the Sun (in circles).



Which Explanation is "Correct"?

- **Both theories "explain" the irregular motion of the planets.**
  - **Ptolemy: Earth at center of universe. Motion of planets described by circles upon circles.. Earth still at center of universe.**
  - **Copernicus: Earth just a planet just like other five planets. All go around sun. The strange motion of the planets (retrograde motion) is explained --- almost --- still must have circles on circles to describe detailed motion.**
- **Which Agrees Better with the Data?**
  - **At the time of Copernicus, there was NO BIG DIFFERENCE between the match between either theory and the data!**

Johannes Kepler (1571-1630)

- **The early years (Weil der Stadt, Germany):**
  - **Grim.. 1 of 7 children, 3 died in childhood.**
  - **Protestant, able to attend college & study theology**
- **First position (1594): teaching math at Gratz**
  - **Official duty: astrologer.. successes: predicted a cold wave & the invasion of the Turks!**
  - **Avowed Copernican.... Neoplatonic philosophy driving force.. sun worship, even.**
  - **Wrote Cosmographical Mystery (1595)**
- **Left Gratz (religious problems) in 1600 for Prague**
  - **Collaborates with the great astronmer Tycho Brahe; Upon Brahe's death (1601), becomes Imperial Mathematician**
  - **Uses Brahe's data on orbit of Mars to "solve the Problem of Planets" and writes New Astronomy (1609)**
  - **Puts forth many "laws" in Harmonies of the World (1619)**

The Holy Roman Empire at the time of Kepler

People and Events Contemporary to Kepler (1571-1630)

Nicolas Copernicus 1473--------1543
De Revolutionibus by Copernicus 1543
Tycho Brahe 1546------1601
Galileo Galilei 1564---------1642
William Shakespeare 1564------1616
Johannes Kepler 1571------1630
Defeat of Spanish Armada 1588
Discovery of Australia by William Janszoon.1606
Jamestown established 1607
Telescope invented by Johann Lippershey ...1608
King James Version of The Holy Bible 1611
Thirty Years War 1618--1648
Pilgrims landed at Plymouth 1620
Dutch bought Manhattan for $24.00 1626
Taj Mahal built.....1632-45
Harvard College founded 1636
Isaac Newton 1642----------1727
Reign of Louis XIV 1643---------1715

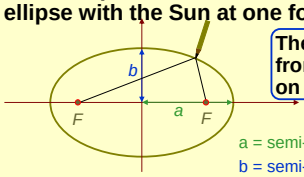
From: http://www.kepler.arc.nasa.gov/johannes.html

New Astronomy (1609)

- **Kepler spent almost 10 years trying to determine the orbit of Mars from Tycho's data.**
- **Using compounded circles, his best effort got agreement within 8' of arc (1/4 of moon's diameter)..... much better than any previous solution..**
  BUT Tycho's data claimed 4' of arc accuracy.
- **Solution: ABANDON PARADIGM OF UNIFORM CIRCULAR MOTION!!**
- **Two Changes:**
  - **PATH: elipses instead of circles**
  - **SPEED: not uniform - varies with the time of year (departure from Platonic ideal of circles)**

Kepler's First Two Laws

- **PATH: A planet travels in an orbit which is an ellipse with the Sun at one focus:**

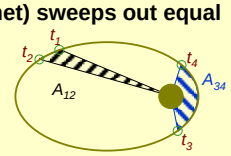


The sum of the distances from two "foci" *F* to a point on an ellipse is a constant.

a = semi-major axis
b = semi-minor axis

- **SPEED: A planet travels at such a rate that the radius vector (sun to planet) sweeps out equal areas in equal times.**

$A_{12} = A_{34}$
if $t_2-t_1 = t_4-t_3$



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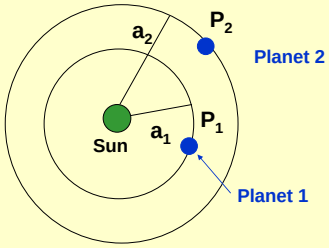
Kepler's Third Law

- Relates the orbit period P of a given planet to its distance a from the sun

P^2/a^3 = constant
where the constant is the same for all planets



Kepler's Third Law

- This Law (unlike the first two) ties together the motions of different planets

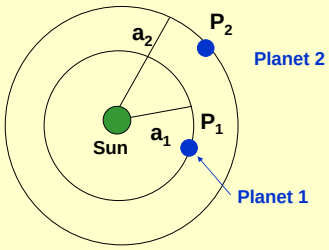
P^2/a^3 = constant

Planet	Radius (a in AU)	Period (P in yrs)	P^2/a^3
Mercury	0.387	0.241	1.002
Venus	0.723	0.615	1.001
Earth	1.000	1.000	1.000
Mars	1.524	1.881	1.000
Jupiter	5.203	11.862	0.999
Saturn	9.534	29.456	1.001

Newton will explain why this works. . . .

Exercise

- If planet 2 is twice as far from the sun as planet 1, what is the ratio of the period of planet 2 to that of planet 1?



Galileo & the Telescope

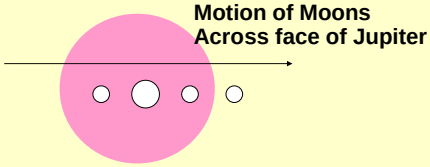
- Remarkable story of how science works
- 1609 -- Kepler's Book "New Astronomy" Published
- April, 1609 Telescope first demonstrated in Holland
- May -- Galileo hears about telescope
- June -- Galileo has working 3 power model
- Summer -- first observations of the sky
- Autumn -- observing moon
- Jan. 9-15, 1610 -- first observation of moons of Jupiter
- April, 1610 -- Publication of "Starry Messenger" in Venice
- Summer, 1610 -- Confirmation by Kepler

Galileo & the Telescope

- The Starry Messenger (1610)
- Discoveries revealed in this book:
  - The size of the stars are NOT magnified, but there are many stars unseen by naked eye.. Supports larger universe
  - Moon's topography similar to that of Earth.
  - Observed sunspots (something temporary in "immutable" heavens)
  - Observed 4 moons of Jupiter (motion around a different center!)
  - Observed phases of Venus -- Supports sun-centered system of Copernicus and Tycho -- Eliminates earth-centered system of Ptolomy.

Galileo & the Telescope

- Moons of Jupiter
- Another "solar system" - motion about a different center



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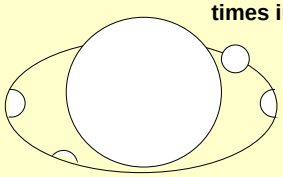
Galileo & the Telescope

- Phases of Venus
- Observation through telescope shows bright and dark sides of Venus
- Clearly orbiting the sun -- not the earth!

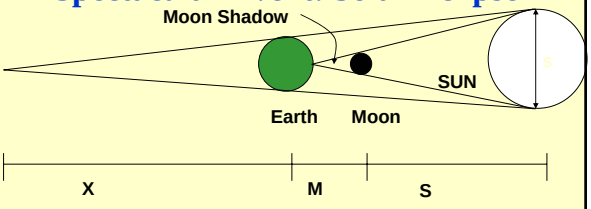
Venus at different times in its "year"



The Copernican Revolution

- Sun Centered System of Planets
- The earth is just a planet
  - Deep philosopical implcations
  - The Church Forbids Galileo's teaching - places him under house arrest (ca. 1640).
  - Not until 1820 does the Church admit that Galileo was correct.
- First real quantitative description by Kepler
  - Planets move in ellispses
- Illustration of how new observations can suddenly reveal truths
  - Phases of Venus, Moons of Jupiter reveal directly a planet orbiting the sun, moons orbiting a planet

Spectacular Event: Solar Eclipse



- The moon appears to just cover the sun during an eclipse, then from geometry S/s = M/m

(as we noted earlier)

Solar Eclipses

- Solar eclipse maps --- from the site http://sunearth.gsfc.nasa.gov/eclipse/TSE1999/TSE1999.html

Illinois witnessed an eclipse in 1999 – will be a great eclipse site in 2017 and 2024

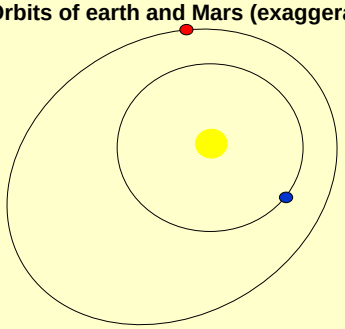
Kepler Trivia

- Kepler quote: "These eclipses are expensive things!"
- When a total solar eclipse occurred in Austria, Kepler set up an observation point in the town square.
- During the darkness someone stole his wallet!

- The solar eclipse of 1999 was total in Kepler's home town Weil der Stadt, Germany

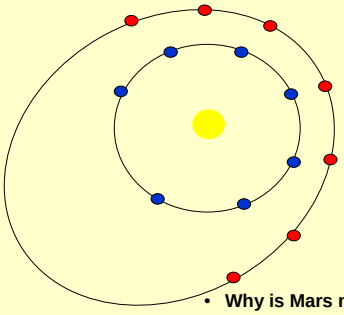
Mars – Earth - Sun

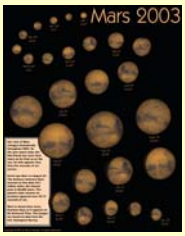
- Closest approach in 60,000 years
- Orbits of earth and Mars (exaggerated)



Mars - 2003

- Orbits of earth and Mars (exaggerated)





- Why is Mars near the full moon now?

Summary

- What do we really see in the sky?
  - Sun, Moon, Stars appear to rotates around the earth
  - Just from observing the sun from the earth one cannot distinguish between descriptions with the earth at the center or the sun at the center!
  - Which explanation is simpler? More useful?
- Problem of the Planets
  - The strange motion of the planets is an esoteric effect of no practical consequence for people --- yet it is crucial in the story of science competing world views of enormous philosophical and practical importance
  - Astrology treats the motion as somehow related to life on earth - leads to fortune telling, horoscopes, ….
  - Astronomy searches for explanations in simple laws - Leads to new science - Kepler's Laws - crucial for Newton's theory - Next

Next Time

- Start Newton's Laws
  - Epitome of Classical Physics
  - Built upon the work of Galileo, Kepler, others
- Reading
  - March, Chapter 2, p 23-29; Chapter 3
- Homework
  - Homework 2 due Wed. Sept. 17
  - Problems are on Kepler's laws and the first steps of Newton's laws