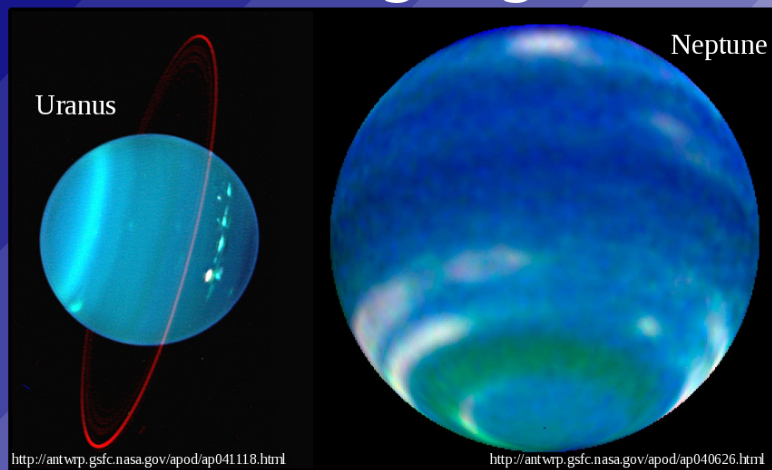
Uranus and Neptune

the other gas giants



Astronomy Dept. Public Night * Feb. 5, 2010 * 8:00 pm, 451 Tate

5a: So, what was wrong with Ptolemy's model to a contemporary mind?

First, everything was an accident.

That is to say that each planet had its own special "deferent" circle (i.e. guiding center circle) and its own special epicycle radius and period.

For each planet, you needed to come up with the following completely unrelated and arbitrary parameters:

1. The radius of its deferent circle, that is, of the orbit of its guiding center about the earth.
2. The displacement of the center of the deferent circle from the earth.
3. The period of its orbit about the deferent circle.
4. The radius of its epicycle.
5. The period of its orbit about the epicycle.

There was no way to establish, within the model, a necessary ordering of the sun, moon, and planets in terms of their distances from the earth. The same observed positions on the sky could be explained by multiplying both the radius of the deferent and the radius of the epicycle by a common factor. The distances from the earth cannot therefore be determined in this model and are hence arbitrary. The work of an arbitrary-minded god?

5b: So, what was wrong with Ptolemy's model to a contemporary mind?

One also had to explain the following amazing coincidences:

1. The guiding centers of the epicycles for both Mercury and Venus revolve about the earth at ***precisely*** the speed of the sun's orbit.
2. These guiding centers are both ***always*** located on the line joining the earth and the sun.
3. The periods of the motions about the earth of ***ALL*** the guiding centers of the planets are identical to the period of the motion of the sun about the earth if we choose for the outer planets to generate their motion using big epicycles traveling on small deferent circles rather than the other way around. (That is, we must explain why it is possible to build a model like Tycho Brahe built, that produces the same motions but in which all the epicyclic guiding center periods are identical.)
4. If we generate motions for the outer planets using small epicycles, as Ptolemy did, we need to explain why all the periods of the motions of the outer planets about their epicycles are identical and equal to the period of the sun's motion about the earth. (That is, we need to explain why the sun's period should be involved at all here, since the motions of the planets around the earth have nothing to do with the sun in Ptolemy's model.)

Outline of Lecture on Copernican Revolution:

5b: So, what was wrong with Ptolemy's model to a contemporary mind?

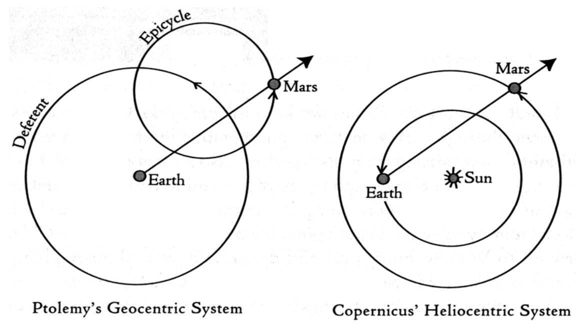
In short, Ptolemy had an awful lot of explaining to do.

Usually, when a scientist is looking for a mechanism that can explain a collection of observations, coming upon such an apparently accidental equality of seemingly unrelated numbers is an important clue to the solution to the problem.

It is often a sign that these numbers come out to be the same for a reason that is fundamental to the mechanism that creates the observed phenomena.

Modern scientists are now familiar with this, but in Ptolemy's time the clue might have been more easily missed.

But the fact that the Greek's were aware that a heliocentric model could naturally produce the observations suggests that the coincidences had indeed caused people to question and to think.



In Ptolemy's model, on the left, the guiding center of Mars' epicycle orbits the earth on the "deferent" circle. We need to specify the radii of the deferent and of the epicycle, which must have a special ratio but which can both be scaled together arbitrarily. We must also specify the orbital periods for both the deferent and the epicycle.

In the Copernican model, we must specify only the ratio of the orbital radii of Mars and the earth as well as the ratio of their orbital periods. Two arbitrary constants are eliminated from Ptolemy's model, the radius of the deferent for Mars and one period (which is replaced with the period of the earth's orbit). An epicycle disappears in the process as well.

If we consider the motion of only a single planet, like Mars, which is shown here, Ptolemy's model does not seem much more complicated than Copernicus'.

However, when we take the motions of all the 5 other known planets at the time, Copernicus had a very much simpler construction.

He eliminated all of Ptolemy's large epicycles and explained the equality of all their periods, for the outer planets, and the periods of their guiding centers, for the inner planets.

Details remained in both models. These result because the actual planetary orbits are elliptical and not circular.

Ptolemy dealt with this using uniform motion about the equant point for an eccentric (displaced) deferent circle, and Copernicus dealt with it by introducing a small epicycle for each planet.

As a result, the 2 models were equally inaccurate (since both were wrong), but Copernicus' model was much more appealing. This appeal was not purely aesthetic; its improved construction led the way to revisions that later produced a correct model and suggested the mechanism of gravity.

Thus Ptolemy's model, in which so many things appeared arbitrary or accidental, led nowhere and proved a scientific dead end.

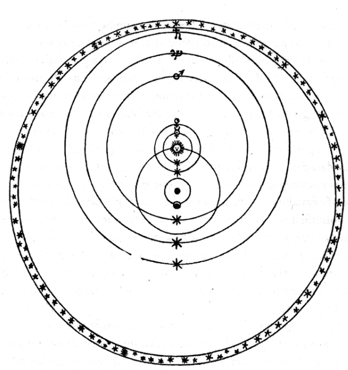
But Copernicus' model produced a framework for thought in which it was soon possible to correct the inaccuracies through a slight modification (circles became ellipses).

The model also exposed tantalizing trends in the radii and periods of planetary orbits, and these helped to lead later scientists to uncover the underlying mechanism driving the motions, the force of gravity.

Thus Copernicus started out along an extremely fertile path of discovery.

Copernicus' model clearly had an impact on other scientists, but the fact that no star showed any parallax called the motion of the earth in the model into question.

"EMBELLISHED BY A DISTINGUISHED MAN"



Tycho Brahe's geoheliocentric system from his De mundi aetherei recentioribus phaenomenis *(Uraniborg, 1588).*

Brahe invited the young scientist Kepler to come work with his detailed observations in order to sort this out. (More on Kepler later.)

A diagram of the solar system made by Tycho Brahe in 1588.

The identical orbital periods of the sun, Mercury, and Venus are explained by these two planets orbiting the sun as it in turn orbits the earth.

In this picture, the sun carries along Mars, Jupiter, and Saturn as well. The role of the sun is clearly influenced by Copernicus' ideas, but in this model of Tycho's the earth does not move. Tycho believed that the earth was stationary because he could not observe any parallax of any star.

Outline of Lecture on Copernican Revolution:

5c: So, what was wrong with Ptolemy's model to a contemporary mind?

Third, the planets do not move along their circular deferents at uniform speeds.

- This may not sound like a problem to you, but it did to the 16th century intellectual.
- The idea of Aristotle was that if a given motion is forever, then it must be constant.
- We believe this too, but for us the only such motion is in a straight line at constant velocity. This concept of ours comes from Galileo. It is the concept of inertia. For us, the motion of the earth is constantly being changed by action of the sun's gravity (and other, lesser gravities).
- For Aristotle, uniform circular motion seemed like something that could go on forever without change and, as it were, without any need for constant special attention (of a deity or other agent).
- But in Ptolemy's model of the solar system, the planets do not move along their guiding center circles at constant speeds. This suggests that something (someone? a god?) is constantly pushing and pulling them along, causing them to speed up and slow down in a regular fashion. This need was viewed as a flaw in the model.

Outline of Lecture on Copernican Revolution:

5c: How did Copernicus address these flaws of Ptolemy's model?

He replaced the **non-uniform** motion of the guiding center of Ptolemy's epicycle about its circular orbit with **uniform** motion about a circle and **uniform** motion about a small epicycle.

He eliminated the large epicycles in Ptolemy's model in favor of the motion of the earth about the sun. This made all the motions much simpler.

He explained the retrograde motion of the outer planets as the natural result of the earth's motion and the parallax that it causes.

(He did not explain why we observe no parallax of any star, although we do see parallax of planets. Tycho Brahe, who looked very carefully, could not see any parallax of any star, and therefore concluded that the earth cannot be moving. This problem with Copernicus' model was not resolved until the invention of the telescope, which showed that the nearest star is too distant to have its parallax observable with the naked eye.)

Copernicus was able to remove much of the unappealing arbitrariness of Ptolemy's model. He showed that in his new heliocentric model one can compute the radii of the orbits of the other planets in terms of the radius of the earth's orbit, and that their orbital periods fall into a very regular progression with increasing orbital radius.

Copernicus' model of the solar system, like Ptolemy's, required the planets to move on epicycles as they orbited.

Copernicus' epicycles were very much smaller than Ptolemy's, and the motion of the guiding centers of these epicycles was uniform, unlike the guiding center motion for Ptolemy's epicycles.

In these ways, Copernicus' model was superior, because it involved only UNIFORM circular motion (around the epicycle and of the epicycle around the earth), while Ptolemy needed to have non-uniform motion of his epicycles around the earth. But this was a detail with an appeal mainly for experts rather than "the person on the street" at the time.

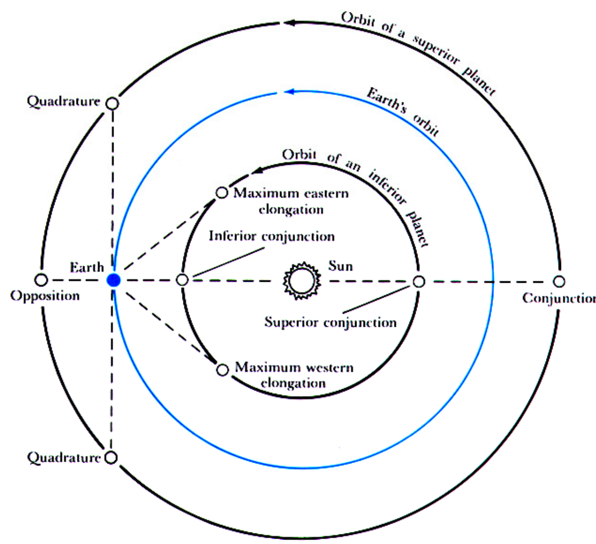
Copernicus' model could not be used to make more accurate predictions than Ptolemy's. It's main appeal was that it was simpler and did not require the planets to execute such unusual paths in their orbits. In addition, unlike Ptolemy's model, it allowed us to determine the radii of the planets' orbits about the sun (in units of the radius of the earth's orbit).

Role of Copernicus:

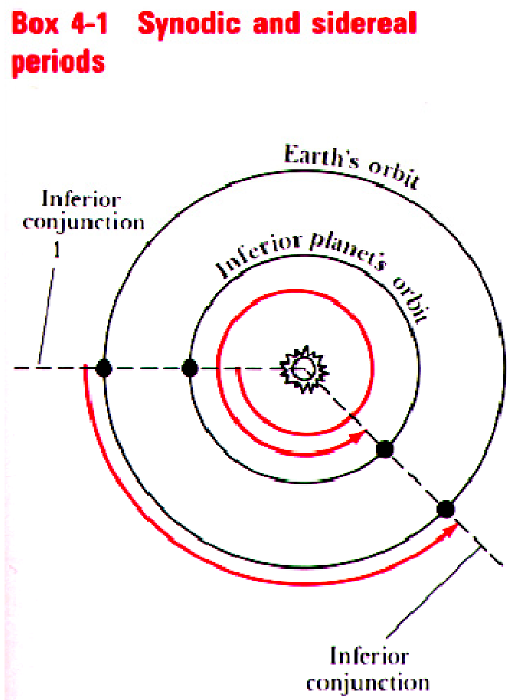
12. Nicolaus Copernicus, born in Poland in 1473 (to a wealthy family), decided in the early 1500s to try to simplify the Ptolemaic model by putting the sun at the center.
13. Radii of planets from the sun
    a. Determined by elongation angles.
    b. Results were good to 1% for all but Saturn.
    c. Ptolemaic model cannot determine these radii.
14. Introduced small epicycles to get varying orbital speeds.
15. *De Revolutionibus Orbium Celestium*, published in 1543, the year Copernicus died.
16. Circular orbits required epicycles, so still inaccurate.
17. Therefore not adopted, but this model was VERY influential on later developments.

Copernicus

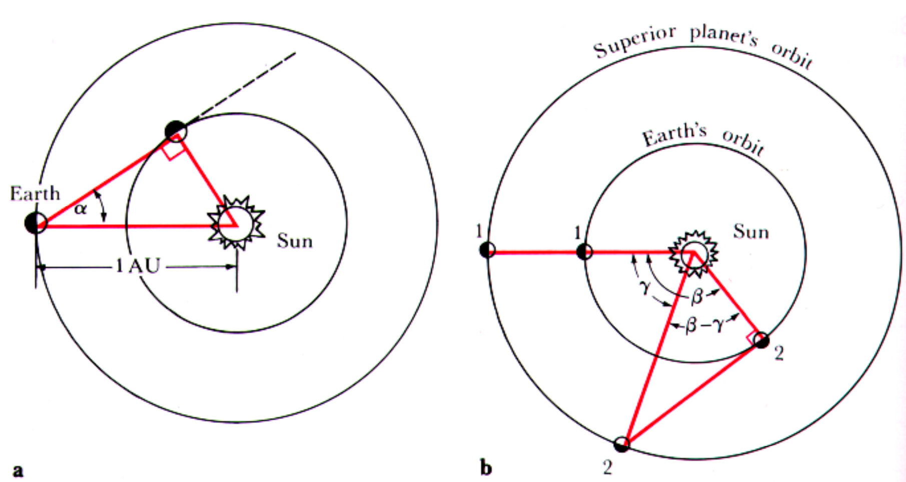
Figure 4-4 Planetary configurations *The key points along a planet's orbit are shown in this diagram. These points identify the specific geometric arrangements possible between the Earth, a planet, and the Sun.*



Copernicus figured out that observations of the elongation angles of planets could be used to determine which orbited nearer and which farther from the sun.



Copernicus figured out how to calculate the sidereal period of a planet's orbit from its synodic period (the period observed from the orbiting earth).



Copernicus figured out how to use right triangles to determine the orbital radii of the planets.
He got the radii of all but Saturn's orbit to 1% accuracy.

A wonderful feature of the Copernican model emerged:
there is a natural progression of orbital period with radius from the sun.

The closer a planet is to the sun, the shorter is its orbital period. This makes sense if somehow the sun is creating the force that causes the orbital motion.

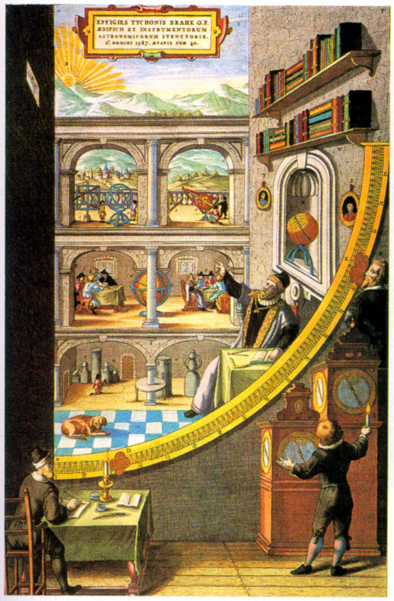
In this model, the very distant stars orbit most slowly, essentially not at all.

In the Ptolemaic model, however, the distant stars appear to orbit the earth more rapidly even than the moon.
This is not appealing, since they are never observed to pass in front of the moon, and therefore must be more distant. In the Ptolemaic geocentric model, objects orbit the earth more slowly as they become more distant, until we get to the most distant objects, the stars, which orbit the earth most rapidly.

Role of Tycho Brahe:

18. New, detailed observations of the planetary motions obtained, with the naked eye, by Tycho Brahe (1546-1601), a Danish nobleman, over 30 year period.
19. Accurate to one arc minute.
20. Found no parallax of any star.
    a. Earth must be stationary.
    b. Copernicus must have been wrong.
    c. Largest stellar parallax is *actually* about one arc second.
    d. Nearest star is really far away from us.
21. Tycho charged his assistant, Johannes Kepler, hired in 1600, a year before Tycho's death, to analyze his data, so that he should not have worked in vain.

[6-10]



Tycho's naked-eye observatory

Tycho Brahe

vented shortly after his death, Tycho's data remai
the best set of naked-eye observations ever made
Despite the quality of his observations, Tycho
never succeeded in coming up with a satisfying e
planation for planetary motion. He did, however,
succeed in finding someone who could: In 1600,
hired a young German astronomer named Johanr
Kepler (1571–1630). Kepler and Tycho had a stra
relationship while Tycho was living.[8] But in 1601
as Tycho lay on his deathbed, he bequeathed all
notebooks of observations to Kepler and begged
to find a system that would make sense of the ob
vations so "that it may not appear I have lived in v

<u>Role of Johannes Kepler:</u>

22. Kepler tried to fit circular orbits to Tycho's observations.
    a. Mars most difficult.
    b. Best circular orbit deviated from Tycho's observations by no more than 2 arc minutes, except for two isolated observations, for which the deviation was 8 arc minutes.
    c. Kepler's refusal to ignore these 2 observations, and Tycho's care in making them, which made them unignorable, are key features of science, as opposed to the many activities that seek the respect accorded to science without having to submit to the rigor of the scientific method.
    d. Kepler was able to fit all Tycho's observations by using elliptical, rather than circular, orbits.

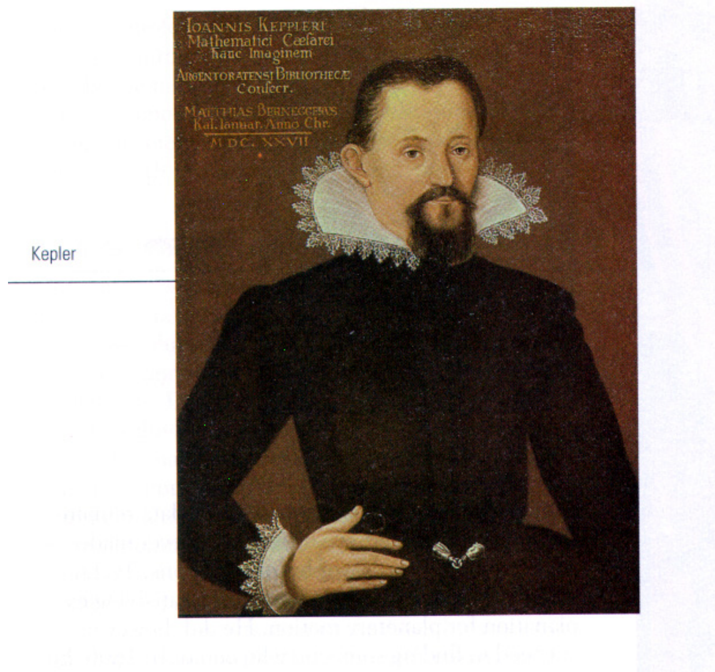


Figure 6.8b Drawing an ellipse **39**

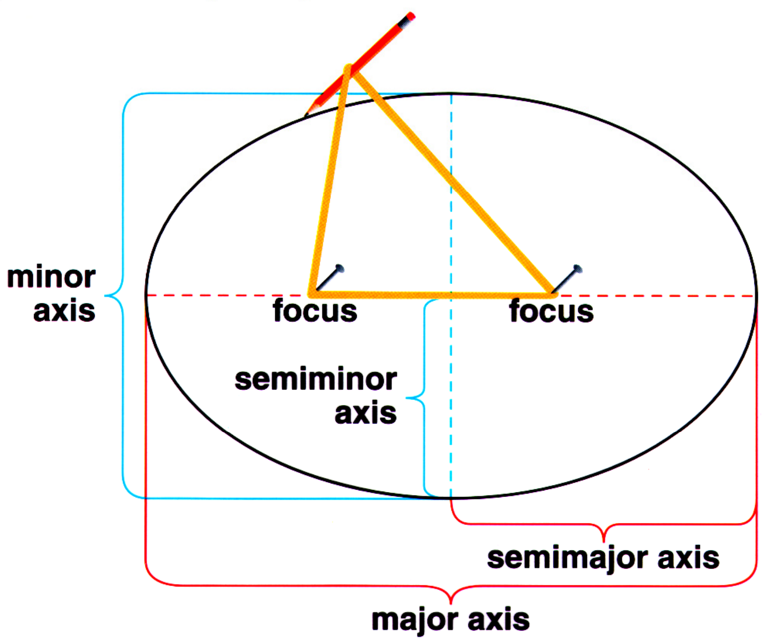
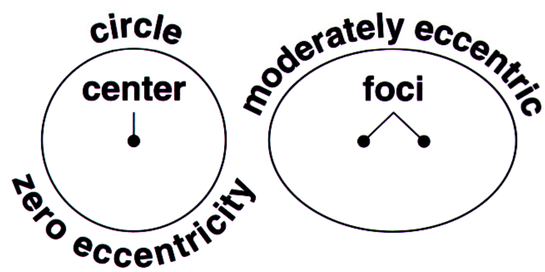
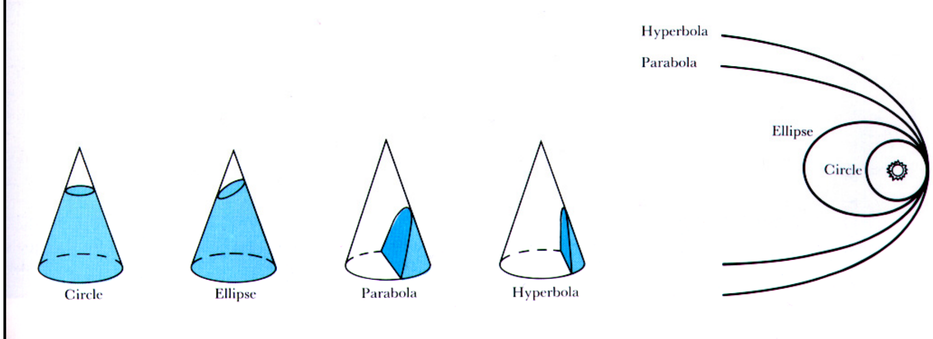


Figure 6.8 c Explaining eccentricity





An ellipse is one member of a family of curves, called conic sections.
Newton showed that the most general orbits are conic sections, either circles, ellipses, parabolae, or hyperbolae.

To do this, he needed to invent the calculus; one of the greatest mathematical advances of all time.

Outline of Lecture on Copernican Revolution:

23. Kepler's three laws of planetary motion:
    a. The orbit of each planet about the sun is an ellipse, with the sun at one focus.
    b. As a planet moves along its orbit, it sweeps out equal areas in equal times.
    c. $(\text{orbital period, in years})^2 = (\text{average distance, in AU})^3$
24. First two laws predict changes in speed without epicycles.
25. Third law relates distance from sun and orbital speed.

The CD that comes with your textbook illustrates the 3 laws.

Your textbook says these laws are "empirical" and do not explain "why" the planets move the way they do, while Newton's laws do. Not so. Newton's laws are just as "empirical." But they describe more phenomena with a simpler mechanism.

Figure 6.9 Kepler's first law **40**

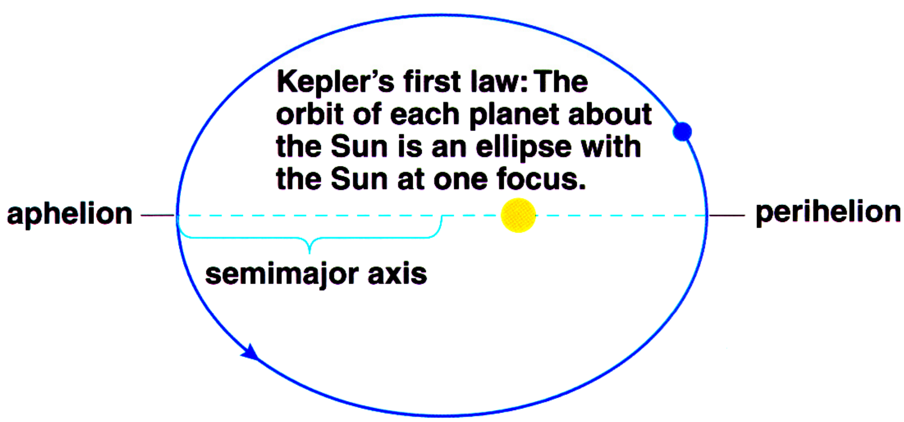
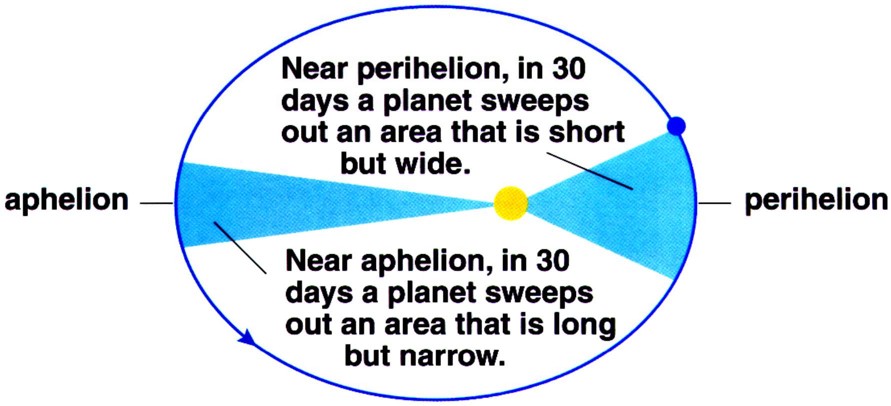


Figure 6.10 Kepler's second law



The areas swept out in 30-day periods are all equal.

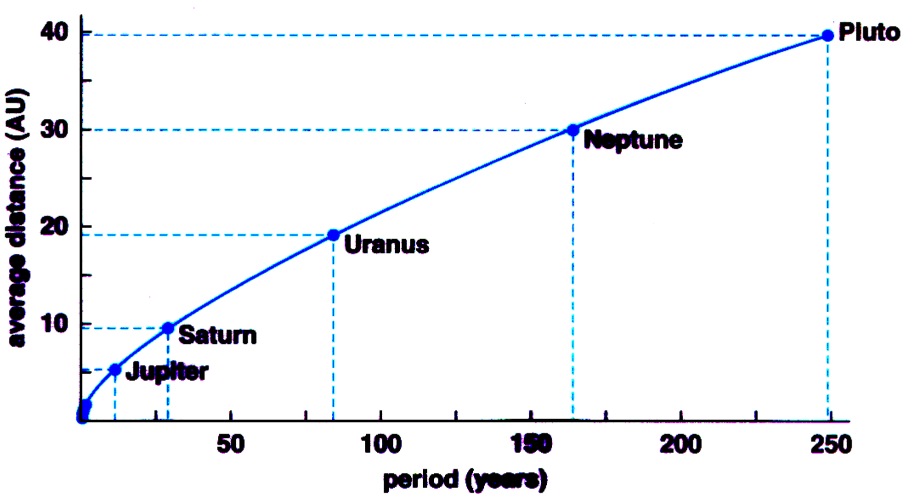
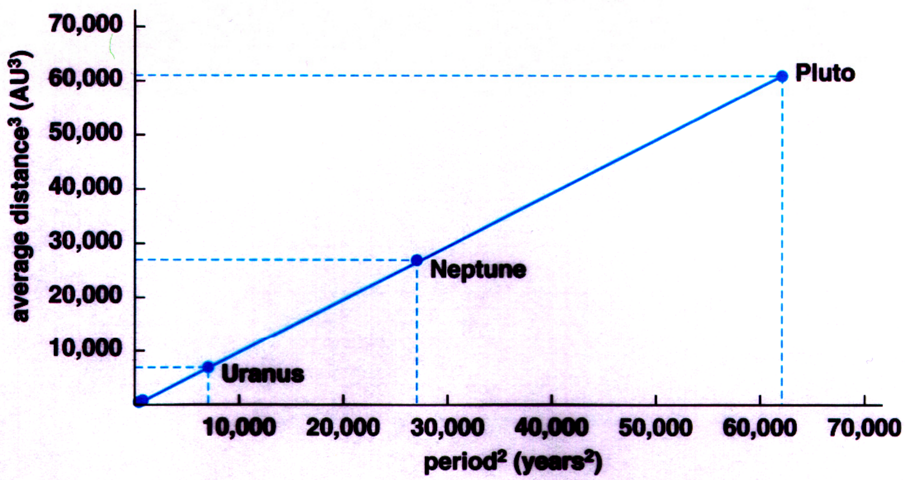


Figure 6.11 a&b Kepler's third law and a plot of average distance against orbital period 41



Outline of Lecture on Copernican Revolution:

26. Kepler's work has several properties that, in science, signal discovery of the right track.

   a. It permits, in fact it forces, the precise calculation, without any additional assumptions, of aspects of the system that before had been arbitrary.
   (*the distances of the planets from the sun*)

   b. It reduces the number of parameters in the model for which values must be specified in order to match the observed phenomena.
   (*Although each orbit now has an eccentricity as well as a semi-major axis (average distance from the sun), only these two numbers are needed to fit the data, in place of the earlier theory's radii of orbit and epicycle, location of the center of the orbital circle, and speeds of motion along both orbit and epicycle.*)

Outline of Lecture on Copernican Revolution:

27. Kepler's work has several properties that, in science, signal discovery of the right track.

    c. The theory makes *predictions* that can be tested concerning other as yet unobserved situations (for example, cometary orbits).

    d. Usually, a new theory that represents a conceptual breakthrough, like Kepler's theory, unexpectedly *and unintentionally* solves some long-standing and vexing problem.

28. Kepler's system did away with the epicycles of both the Ptolemaic and the Copernican models. This was a great simplification, but there was still more to come, stimulated by the revelations of Galileo, who injected stunning new information by using the telescope, recently invented, to observe the heavens, beginning in 1609.

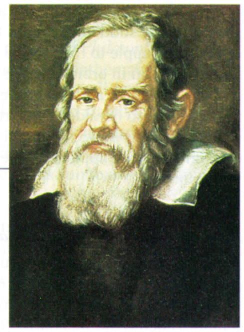
Outline of Lecture on Copernican Revolution:

29. Galileo upset established beliefs with his observations using the telescope in several ways:

    a. He observed sunspots, imperfections of the solar surface.
    b. He observed mountains on the moon, imperfections as well
    c. He observed the phases of Venus, which demonstrate that it orbits the sun, not the earth.
    d. He observed four "stars" orbiting the planet Jupiter, which caused a sensation.

30. Items c and d above caused near unanimous adoption by the scientific community (such as it was) of the heliocentric model of Copernicus and Kepler by the mid 1600s.

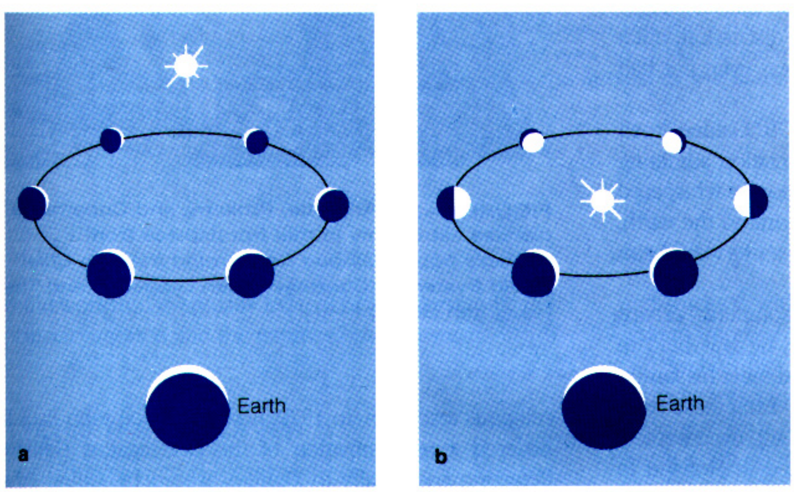
31. In 1687, Newton, in his *Philosophiae Naturalis Principia Mathematica*, explained all of Kepler's laws (and much more) with a single concept, universal gravitation.

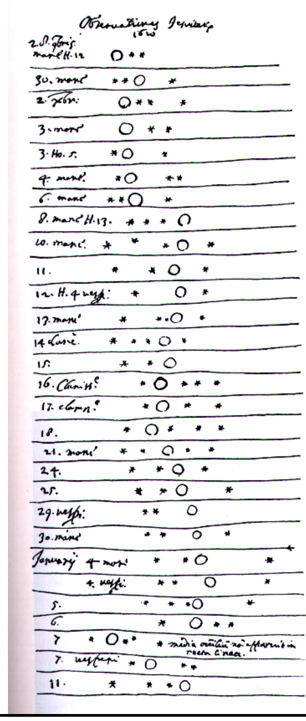


Galileo

FIGURE 6.12 The shadows cast by mountains and crater rims near the dividing line between the light and dark portions of the lunar face prove that the Moon's surface is not perfectly smooth.

scope, he saw sunspots on the Sun, which were considered "imperfections" at the time. He also used his telescope to prove that the Moon has mountains and valleys like the "imperfect" Earth by noticing the shadows cast near the dividing line between the light and dark portions of the lunar face (Figure 6.12). If the heavens were not perfect, then the idea of elliptical (rather than circular) orbits was not so objectionable.





Galileo's observations of Jupiter's moons.

Figure 4-10 Galileo's observations of Jupiter's moons *In 1610, Galileo discovered four "stars" that move back and forth across Jupiter from one night to the next. He concluded that these are four moons that orbit Jupiter much as our Moon orbits the Earth. (Yerkes Observatory)*

Jupiter with its four Galilean satellites

Outline of Lecture on Copernican Revolution:

32. Galileo's work on the motion of bodies (on the earth) laid the groundwork for Newton's amazing synthesis, which produced Newton's 3 laws of motion and of universal gravitation:
    a. He developed the concept of *inertia*:
        1) Aristotle had asserted that all bodies tended toward their most natural state – a state of rest.
        2) Galileo said that a body in uniform motion (i.e. at a constant speed in an unchanging direction) would, by its *inertia* resist any change in that motion and hence remain in uniform motion unless acted on by a force.
        3) Newton adopted this law of inertia as his 1st law of motion.
        4) Galileo asserted that the behavior of bodies follows the same laws in any *inertial* frame of reference.
        5) Transforming our view point from one such frame of reference to another is now called a *Galilean transformation*.
        6) The invariance of the laws of motion under Galilean transformations is called *Galilean invariance*.

Outline of Lecture on Copernican Revolution:

    b. He demonstrated that bodies of all masses fall toward the earth at the same speed. (Leaning tower of Pisa.)
    This observation helped determine the form of Newton's law of gravitation. (We will see how later.)

33. Galileo's tract, *Dialogue on the Two Great World Systems*, published in 1632, set out the arguments for the heliocentric model in a format that did not unequivocally commit Galileo to either view, but this was not enough to keep him out of trouble.
    a. Apparently Galileo could not resist putting the standard arguments in the mouth of Simplicio (an obvious simpleton).
    b. The book was written in the vernacular, and was popular.
    c. Galileo, despite his powerful friends, was put under house arrest, after first recanting his beliefs publicly.

Outline of Lecture on Copernican Revolution:

34. Despite Galileo's enormous advances in understanding, it was Newton who performed the vital and amazing synthesis:
    a. Newton realized that the laws of motion that apply to balls (or apples) falling to the earth or billiard balls colliding on a pool table are identical to those that apply to and govern the motions of the sun, earth, moon, and planets.
    b. This amazing insight permits one set of simple principles to describe *and predict* the motions of all these things, in fact of every thing.
    c. This set of principles is therefore supported by all observations of all mechanical behavior, and is therefore essentially unassailable.
    d. This is an example of the force of science. To credibly claim that it is not true, you have to come up with an equally voluminous body of evidence. Forget it!

Newton

Outline of Lecture on Copernican Revolution:

35. In 1687, Newton, in his *Philosophiae Naturalis Principia Mathematica*, explained all of Kepler's laws (and much more) with a single concept, universal gravitation.
    a. His theory tied together the motions of the planets with the motion of everyday objects falling to earth.
    b. The gravitational force constant could be measured in the laboratory, and then applied to yield the masses of the planets, information previously unobtainable.
    c. The theory applied to the orbit of the planet Uranus (not in Newton's life time) predicted the location of the then unknown planet Neptune to within 1º.
    d. The theory explained the tides, caused by the gravitational attraction of the sun and moon, as well as the very slow precession of the earth's rotational axis.

Figure 6.14 Newton's law of gravity **42**

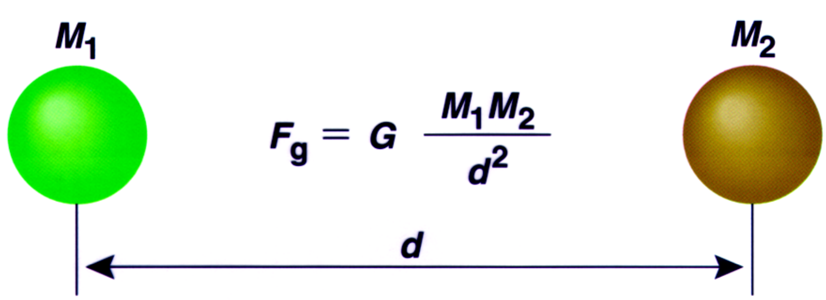


Figure 6.15 Orbits allowed by the law of gravity

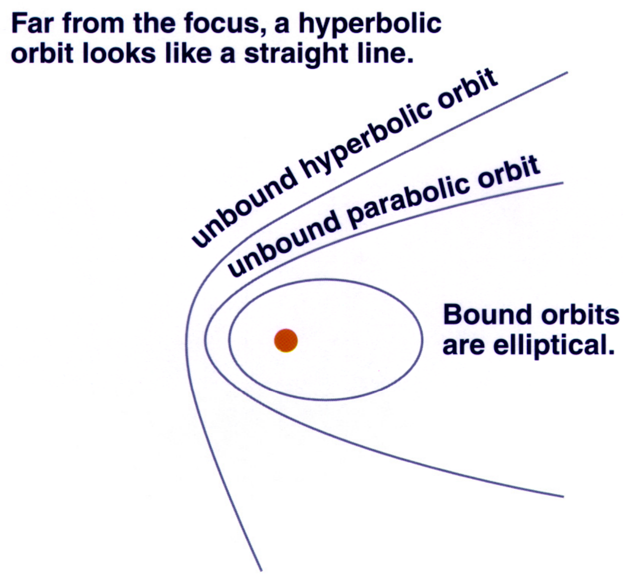


Figure 6.16 Tidal bulges face toward and away from the moon 43

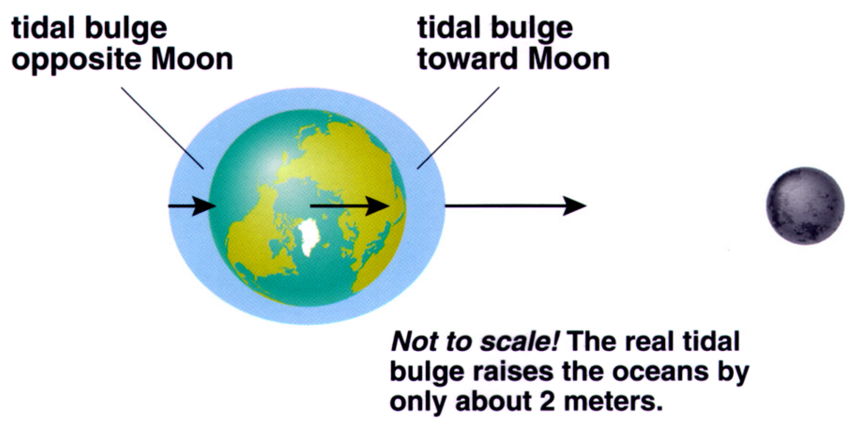
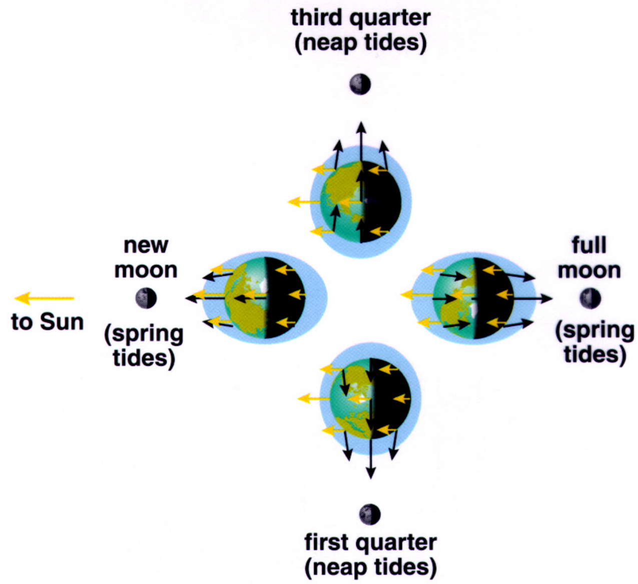


Figure 6.17 Spring and neap tides



Outline of Lecture on Copernican Revolution:

36. The Copernican revolution is a classic example of the scientific method. It exemplifies the following philosophical issues that lie behind the scientific approach:

  a. If two conjectures or theories explain all available objective facts equally well, it is impossible to claim that one is "true" and another "false." Instead, to prefer one of them one must devise a new, objectively verifiable and repeatable experiment, based upon differing predictions of the two theories, and one must be willing to accept the result.

  b. Kepler's laws and Newton's laws make the same predictions for the planetary motions, but Newton's laws are simpler and far more general. Therefore Newton's laws are "better;" they are verified and supported by a vastly larger store of experience and observation.

Outline of Lecture on Copernican Revolution:

36. The Copernican revolution is a classic example of the scientific method. It exemplifies the following philosophical issues that lie behind the scientific approach:

   c. If two models of some phenomenon explain all observations to date, we may believe either one of them is “real.” Only objectively verifiable and repeatable experiments may be used to reject the “reality” of a theoretical model. Since both are equally “real,” it is wise to use the simpler model.

   d. Copernicus’ and Ptolemy’s models, in the light of knowledge in Copernicus’ time, were equally real, but Copernicus’ was simpler.

   e. The models, however, made different predictions for the phases of Venus (unobservable at the time), which later were used to reject one of them.

Outline of Lecture on Copernican Revolution:

37. Let’s think about science and non-science.

   a. Science chooses to address only those questions that can be answered by an objective test of experiment.

   b. In astronomy, because of the paucity of observational data due to the difficulty in collecting it, conjectures abound, but none of these has the force of established theory.

   c. Thus matters of opinion and plausibility are often discussed.

   d. However, all participants agree to abide by the evidence of objective observation.

   e. For example, the Hubble Space Telescope’s “deep field” dispatches the steady state theory of the universe, because it clearly shows that the universe looked different in the past than it looks today. Therefore the steady state theory has been discarded.

Outline of Lecture on Copernican Revolution:

37. Let's think about science and non-science.

f. The textbook's authors, in the first edition, say that when science and tradition or faith come into conflict, science should be silent.

g. However, science, if it can speak to an issue, is willing to make predictions and to stand by them. Science is always willing to submit to objective experiment. This is a reason to consider it more seriously than a framework of belief that will not submit to prediction and objective test.

h. You may think these remarks are related to religion, but in fact there are many reasons, besides arriving at an answer in an area where science cannot provide one, for which one may wish to escape the rigor of the scientific method.

Outline of Lecture on Copernican Revolution:

37. Let's think about science and non-science.

i. Consider, for example, global warming.

j. Or genetically engineered plants as food.

k. Or tobacco.

l. Or marijuana.

m. Or acid rain.

n. Or substitutes for oil as fuels.

38. Science often comes into conflict with political and/or economic interests of all types.

39. An advantage of science as a method is its ability to settle arguments through experiment and demonstration, not through war or deceit. Think about it.

Outline of Lecture on Copernican Revolution:

40. Science can be viewed as the study and discovery of things that we can all agree about.
    a. Science is about consensus, not argument.
    b. Science finds concepts that can be demonstrated by experiments that can be performed by anybody (you get the result too, it doesn't only happen when I do the experiment) at any time (not just when I say) and any place (not just in my laboratory).
    c. Scientific concepts grow to be supported by mountains of compelling evidence, so there is no further argument.
41. The agreement that is built by the scientific method is enviable.
    a. Suppose you had a theory that if you and your friends paid no taxes, while everybody else did, everyone would be better off. Wouldn't you like scientific agreement?

Outline of Lecture on Copernican Revolution:

42. The consensus that science builds is so powerful that other endeavors try to capture some of its effects.
    Beware of "science" that is not actually science.
    Accept no substitutes.
    a. Is political science *science*?
    b. What about social science?
    c. Or economics?
    d. Is the law of supply and demand a *law* like the universal law of gravity?
    e. Is Adam Smith's theory of rent a *theory* with the force of the theory of gravity?
43. What a shame it is that science seems to be restricted in applicability to systems that do not interest many of us.