Idea 1: The Earth is not the Center of the Universe

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1 Preamble: The Earth as the Center

Our **first idea** really starts where mankind began the investigation of the natural world. Not suprizingly, for virtually every culture that we have been able to understand through archeology, those first interests in the workings of nature included an attempt at explaining the night sky.

In this first idea, we will study the development of our understanding of astronomy. We begin with the ancient Greeks, although they we by no means the first to try to make sense of the stars. They are, however, the direct ancestors of western civilization, so we will follow that historical development.

It begins at least as far back as Eudoxus who recorded the idea of the entire universe surrounding Earth. This picture is given in Fig. 1.

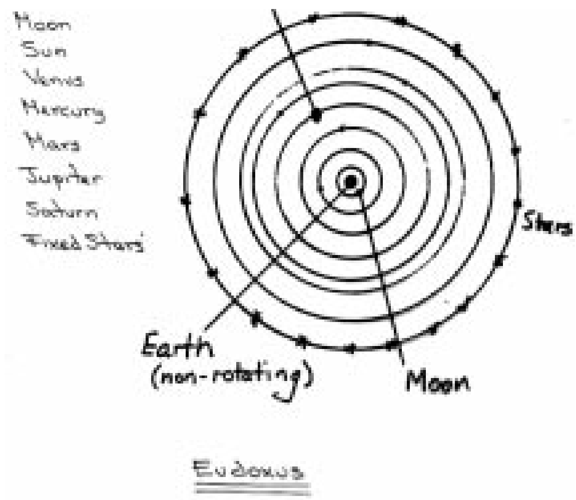


Figure 1: Eudoxus (Greek) provides the first recorded geocentric model.

2 Theories of Nature and the Universe

For all of recorded history, the stars have fascinated mankind. It has been the source myth and scientific study. In the history of man, it was the search for understanding the Cosmos, which heralded the beginning of science, as we know it today.

- Prehistoric: Purely Mystical
- Aristotle
- Ptolemy
- Copernicus
- Kepler
- Newton
- Einstein

The progression of knowledge from basically "wrong" ideas to basically right ideas took 2000 years, from 300 BC to 1700AD. At each stage, some essential element of the final understanding was added by each scientist/philosopher from Aristotle to Kepler. Kepler finally identified the "law" governing motions of the heavens. He did not know why they moved like that - why is really the second idea and based in Newton's laws. Still later, Einstein showed there was a bigger picture than Newton saw. That was a shock, but now we understand Einstein actually opened the door to something bigger still. Today, we continue to search for a final pieces of the puzzle that will give us the true "laws" of the Cosmos. That final search is part of our seventh idea.

3 Appearance of the Night Sky

The challenge (to the ancients and to us) is the explanation of what we observe in the night sky. A few salient features are listed below.

1. Stars look like they are all the same distance from us.
2. Stars move, but are fixed relative to each other.
3. Shooting stars are common. (Imperfections in the heavens?).
4. Planets (wanderers) and Sun and Moon move along ecliptic.
5. The Milky Way is a gigantic feature of the sky. (Now, we know that it consists of other stars in our galaxy.)

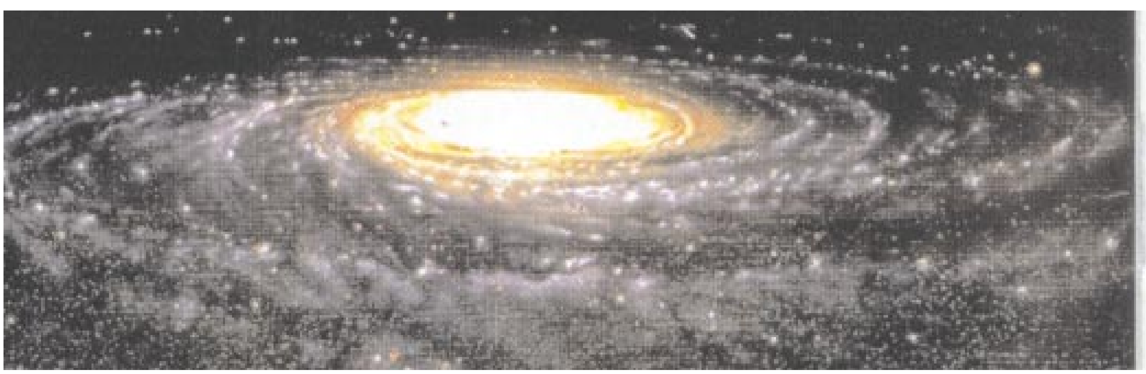


Figure 2: An Accurate Artist's Conception of the Milky Way

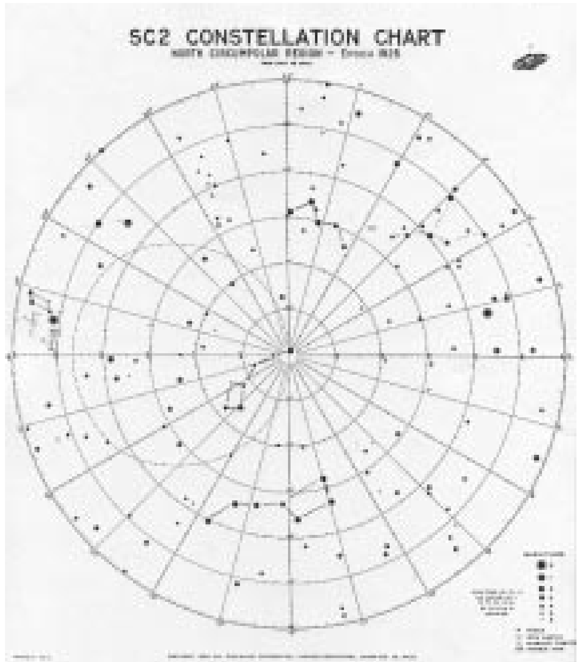


Figure 3: The Top of the Celestial Sphere

Fig. 3 is a drawing of the night sky with the North Star placed at the Center. This mapping of the locations of the stars is called a **sky chart**.

What we observe can be made more specific if we add a few new terms to our vocabulary.

- Celestial Sphere: (Fig. 4)

  Apparent location of fixed stars.
  Polaris is the North Star and does not move.
  Celestial equator is above Earth's equator.

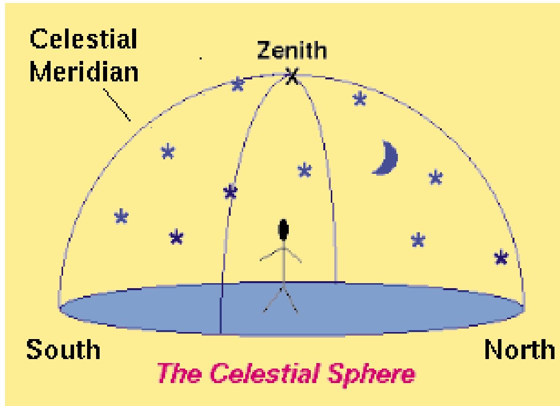


Figure 4: The Celestial Sphere

- Diurnal motion:

  Daily movement of the stars.
  (Rotation of celestial sphere.)

Figure 5: The Celestial Coordinates

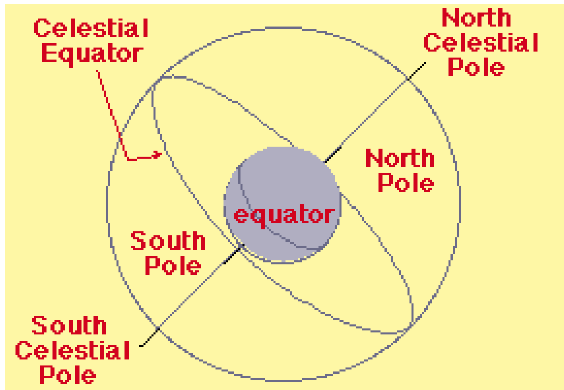
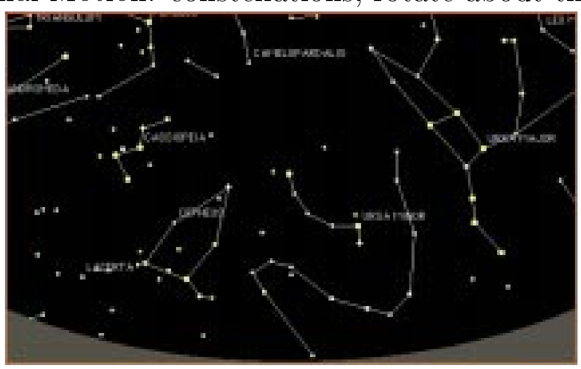


Figure 6: Diurnal Motion: constellations, rotate about the North Star.



- Ecliptic:

  Path of Planets, Sun, Moon.
  (Not exactly on the celestial equator)
  The movements is not exactly on the ecliptic
  and not exactly the same for all.

A time exposure photograph will show the stars moving in concentric circles with the North Star at the center.

Figure 7: A time exposure photograph of the night sky.

4 Observations of the Night Sky to be Explained

There are a few observations which were particularly important and which historically proved key to finding the right explanations.

- Annual Motion:
  - The changing position of the Sun relative to the stars during the course of a year.
  - The Sun's motion is along the ecliptic and this takes one full year.
  - Ecliptic:
- The Moon's trip along the ecliptic occurs every 27 1/3 days.

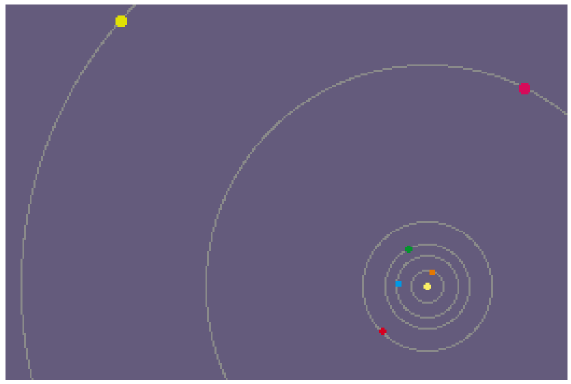
Figure 8: Moon changes throughout each month.

- The Planets' trips along the ecliptic take widely varying lengths of time, from 90 days up to 30 years.
- Retrograde Motion:

  Planets appear to stop sometimes and reverse the direction of motion temporarily.
- Conjunction: Since planets move nearly along the same path at different speeds, they pass one another. When they are on the same location on the ecliptic, they are said to be in "Conjunction". This is considered to be astrologically significant.
- Eclipse (Solar or Lunar):
  - Solar: When the moon passes in front of the Sun and blocks light travelling to earth.
  - Lunar: When the earth passes in front of the Moon and blocks light travelling to it from Sun.

By accident or cosmic design, the Sun and Moon appear to be nearly the same size.

Figure 9: Planets move quickly close to the Sun



5 Aristotle's Concept of the Universe (384-322 BC)

1. Before Aristotle's time, the only explanations of the Cosmos were based on mystic pictures of the world such as a landmass travelling through space on the back of a turtle. Every culture has different legends of their own.

2. Even before Aristotle, the idea that the Earth was round was well established. For 2000 years, even as Columbus sailed from Spain this had been established. While many common people and even established religions argued that the "flat Earth" view was common sense, scholars and navigators of ships (like Columbus) knew the Earth was round. Columbus did not prove this, contrary to what is taught in grade school.

3. Western culture has been fed by Greek origins of these ideas, but native peoples in China, Americas and elsewhere developed their own astronomy.

5.1 Aristotle's Theory of Everything

- Involved both "heaven" and Earth
- It had simple "basics"; everything was made of four (or 5) elements.

  1. Earth
  2. Air
  3. Fire
  4. Water
  5. Ether (not terrestrial)

5.2 Order and Motion of the World was Explained

Ether
$\uparrow$
Fire
$\uparrow$
Air
$\uparrow$
Water
$\uparrow$
Earth

Table 1: Aristotle's Higherarchy of the Basic Elements

Dynamics (motion and change) was a consequence of a tendency to achieve the natural order.

5.3 Aristotle's Explanation of Motion and Change

Because the four basic elements were constantly seeking to arrange themselves in the natural order

(earth $<$ water $<$ air $<$ fire),

we observe motion and change.

- Water runs down hill
- Rocks sink in water
- Bubbles rise
- Chemical change
  - Burning: Wood = air + fire +earth
  - Decay: Elements of Air + water + earth separate

5.4 Aristotle's Explanations of Heavens

Ether, the 5 th element, was only found in the heavens.
It was the "most perfect" of the five. These "perfect" qualities permitted planets to move through the ether without slowing down, i.e. there was no drag, or viscosity to ether. Obviously, it also has the property of transparency, so we could see the stars. Air, had that property too.

Characteristics of Aristotle's mechanical picture of the heavens.

- Planets moved and were carried on spheres like a mechanical clock mechanism.
- Earth resided at the center
- Outermost sphere was the "prime mover"
- Moon, Sun, Planets carried on inner spheres
- 55 spheres in all were necessary for the giant clockwork.

5.5 Failure of Aristotle's Theory

- Unexplained variation (10%) in apparent size of moon during a month.
- Unexplained variation in brightness of planets.
- No quantitative predictions of motion, e.g. where and when to find planets.
- No explanation of retrograde motion.

Aristotle did not really have "data" in the sense of tables of numbers and observations of Heavenly motion. His predictions were correspondingly qualitative. After Aristotle, people learned of good data collected by Babylonian astronomers. The collection of data surely contributed impetus to constructing quantitative theories.

6 Claudius Ptolemy (150 AD)

Ptolemy lived in Alexandria, Egypt around 150 AD. For thousands of years, the Egyptians had been builders and merchants and their culture included a strong religious connection with a type of astrology. Thus, with sufficient interest in predicting the stars, sufficient reason to train members of its society in mathematics and astronomy, there arose an individual who made a great effort to regularize the predictions of astronomy and apply mathematics to the data that was available about the motions of the planets.

Ptolemy

- carried out extensive calculations of astronomical tables.
- wrote the "Almagest" (the "Majestic") with mathematical sophistication.
- was more concerned with accuracy than theory.

Ptolemy produced an elaborate Geocentric (Earth-centered) model where Planets traveled in circles. Circles had been the basis of all descriptions of everyone before him.

To base a description of heavenly motion on circles, a description which he did not understand was flawed, required a rather complex model of circles on top of circles and circular motion superimposed on circular motion.

Ptolemy produced excellent accuracy but a lot of complexity.

6.1 Ptolemy's Devices - Epicycles and More

The complexity of Ptolemy's model was the result of predicting the motion of planets using only circular shapes and circular motion. To do this, he used four "devices" or geometrical constructs.

- Eccentric: Circles not centered at earth.
- Epicycle: A circle on the circle carrying a planet.
- Deferent: Path of center of epicycle (circle).
- Equant: Point about which motion is uniform.

Epicycles, and even epicycles riding on epicycles as in Fig. 12, were part of the description of the motion of planets needed to reproduce the varying speeds and brightnesses (distances). The complex retrograde motion, Sec. 6.2, of planets like Mars made this essential.

6.2 Explanation of Retrograde Motion

When viewed against the background of stars, the paths of planets can sometimes execute backwards motions. Fig. 10 shows the path for Mars.

We must appeal to the correct perspective and first think of how the planets look to each other as they circle the Sun. In Fig. 13 we see Earth passing our nearest neighbor Mars.

From the perspective of an Earth person who would like to believe an Earth-centered model, Mars moves differently when it is close to Earth.

More text is needed distingushing geocentric and heliocentric mechanisms explaining retrograde motion.

6.3 Ptolemy's Theory Successes

Ptolemy's work provided an excellent predictive tool for those few individuals who could understand its complexity. It passes the first test of the scientific method. It is a theory which can be tested.

Most importantly, Ptolemy got all of the qualitative behavior correct.

- Explained Retrograde motion.

  The epicycle, the circle the planet travels on as it moves along the circular orbit, produces backward motion of the planet.

- Varying Speeds

  Variable speed was built into the model in several ways. Certainly the epicycle provides a varying speed, but that needed to be tuned. The equant altered the speed and so did the eccentric.

- Varying Brightness

  To change the brightness, Ptolemy had to change the distance from the planet to the center of its circle. The epicycle provided this along with the eccentric.

  It is not known whether Ptolemy understood that the Sun illuminated the planets. Even if he did, he probably would not have included this in his model. The "inverse square law" for light was probably not properly formulated at the time, and the fact that the planets should be brighter when closer to the Sun or when positioned to reflect more light to the Earth was probably a complexity beyond the capability of the model.

  The brightness was something that was purely subjective. Certainly there was no way to measure the brightness. Nonetheless, the brightness of stars was considered important. A bright star was a "star of the first magnitude" second and third magnitudes were also classified. Today, we still use this terminology with the same basic meaning except today we quantify the measurement and make precise, to the second decimal place, determinations of the "magnitude" of stars.

(Insert table with magnitudes of common stars.)

In addition to qualitative explanations, the truly great achievement was the quantitative ability to predict the where and when of planets and the Sun and Moon. The difficult tests of quantitative predictions were in predicting solar and lunar eclipses and conjunctions. It was the quantitative character that required all the complexity and made it hard to use.

6.4 Shortcomings of Ptolemy's Theory

While excellent, it was not perfect.

- Mathematical Complexity was daunting
- No explanation of why things happened.

  We should appreciate though that he did not provide any wrong explanations of why things happened. Others, at the time, explained the motion of the planets as a consequence of Angels using their wings to propel planets along their paths. That didn't sit with other ideas about the ether, but inconsistency was not grounds for widespread rejection.

  From a modern point of view we might call this a feature of the model. At least it was objective.

- Earth being at the Center was incorrect.

  While this is a shortcoming, it is a problem from our modern perspective. For the time, it was probably more of an essential feature. SO, we can not blame Ptolemy. It was a necessity of the time that the Earth be at the Center.

7 Copernicus and the Heliocentric Model

It was about 1530 that Copernicus arrived at his model of the Sun-centered (heliocentric) universe.

Almost 1500 years had elapsed since Ptolemy. Is this problem so difficult or did something intervene that was more important than astronomy? Well, something intervened. it is called the dark ages. After the time of Ptolemy, came a series of oppressive rulers, restrictive societies and mystic belief systems where science, freedom and honest government were essentially nonexistent. It is estimated that the discoveries of science were delayed by a thousand years because dominant world societies took the path greed and competition for power. If they hadn't, we might be visiting the planets and stars in the year 2000 rather than studying about them from a book. (That last paragraph is my view.)

Copernicus correctly identified the ordering of the planets known then.

- Sun
- Mercury
- Venus
- Earth
- Mars
- Jupiter
- Saturn

There were only five planets known before the invention of the telescope. The more distant planets were discovered, beginning with Hirschel's discovery of Uranus, after 1680, or there about.

- Uranus
- Neptune
- Pluto

Copernicus also correctly deduced that the moon went around the Earth.

Initially, he thought that each of the planets moved in a perfect circle around the Sun. That immediately explained an enormous number of things, but subsequent careful checking showed that their were differences between predictions of times and places and the actual occurrences.

7.1 Advantages of the Heliocentric Circular Orbits

The (circular orbits) heliocentric model had definite advantages

- Simple

  It is a lot easier to calculate positions based on circular orbits around the Sun.

- Explained Retrograde

  Retrograde motion was easily understood in terms of one planet passing the other as discussed in Sec. 6.2.

- Explained Varying brightness

  He was correct in saying that when planets are closer to each other they should appear brighter. This closeness was simpler to see with the Sun at the Center.

- Distances predicted well

  Copernicus had to adjust the size of the orbits (distance from the Sun) to get the predictions of when and where things would be with respectable accuracy. This also meshed with the desire to predict brightness. The distances he choose were quite good compared to modern standards.

7.2 Disadvantages to Copernicus Model

The beauty and simplicity of circular orbits around the Sun did not sweep the astronomical community.

- Not Accurate Enough

  Everything predicted by Copernicus was pretty accurate, but not really really accurate. Being a month off in predicting a conjunctions was devastating because those who believed in astrology wanted better.

- Not Philosophically Pleasing

The community was not really in a position to accept the truth. It was particularly important to the users of astrology that a certain basis for their beliefs was maintained. People needed to believe that the Earth was the center of the universe so that their other belief systems would remain unchallenged.

7.3 Modifications to Copernicus Model

At the risk of spoiling a beautiful model, Copernicus finally decided that planets travelling in simple circles was not sufficient. To achieve greater accuracy, he added circles inside of circles and all the trappings that Ptolemy had used. All except the Equant. To have a point in space where nothing existed controlling the speed of the planet (That's what the equant did.) was an anathema to Copernicus.

His changes increased the accuracy tremendously. Indeed, with more adjustment this model became just as good as Ptolemy's. Unfortunately, it also became complex. Remember, after all these circles inside of circles, one still had to transform the prediction of Copernicus to the point of view of someone one Earth. That's where we live!

8 Compromise Theory

- Obtained new and very accurate measurements

- Measurements showed that both Ptolemy and Copernicus were not completely accurate.

  The "errors" he found in the predictions were quantitative errors. This must be expected since both theories were created to fit known observations. Various parameters had to be adjusted and more accurate data would necessarily mean changes (improvements) in the parameters of the models.

  In principle, the "errors" did not invalidate the models. It would have been possible to put more circles inside of circles and make things more complex to fit more refined data. One must wonder how exasperating this must have been. It already took an enormous amount of time to make predictions because of the complexity.

To make the models better meant making them harder to actually use. There is something wrong with complex models on philosophical grounds. Later, scientists would espouse a minimalist principle saying that correct theories are generally simple theories. This is embodied in the famous quote from Einstein, ”Mother nature may be subtle, but she is not perverse.”

- Proposed ”compound theory” or ”compromise theory”

  Tycho proposed that the Earth be considered the center of the Universe and that the Sun go around the earth, but he used the rest of the Copernican idea and let the planets go around the Sun. The moon still went around the earth.

8.1 Advantages and Disadvantages of Compound (Tycho) Model

Advantages

- Simpler than Ptolemy.
- Explained retrograde motion and other ”basics”
- Distances and other parameters were pretty accurate.
- Esthetically pleasing with Earth at Center.

Disadvantages

- Did not end up being more accurate
- In most respects, this is the same ”model” as Copernicus, just a different point of reference.
- Still complex, including all the weirdness of epicycles, equants etc.

Result was that Brahe did not improve maters with his model, but he did improve matters with his data. The data stimulated a need for a better model.

9 Johannes Kepler 1571-1630

1. Tycho Brahe Assistant
2. Mystic belief in heavenly order (1596 Platonic model)
3. Applied mathematical talents to careful reanalysis of Tycho data.
   (a) Discarded compound theory.
   (b) Tried improving Copernicus with equant and improved parameters.
   (c) Gave up on Copernicus. (Improved results meant added complexity).
   (d) Decided shapes of orbits could not be circles.
   (e) Adopted ellipse as basis of his laws.

Johannes Kepler was a well educated man who started a career as a teacher and scholar. Like many of his day, his scholarly background was a mixture of studies, including mathematics and astronomy. Kepler's interest in astronomy and his belief that there was some mystic explanation to the structure of the Cosmos, led him to Tycho Brahe, whom he convinced to hire him as an assistant. As an assistant to Tycho, he was able to work on a model of the planets based on the five Platonic solids. The "five perfect solids", Fig. 18, had been discovered by Plato who thought them to have mystic significance. Kepler believed that since there were five perfect solids and five planets (Five is all they knew about back then.) there must be a connection.

Kepler believed that if one enclosed each solid in a sphere and then put that sphere inside of another solid and in turn enclosed that solid in a sphere, the process would eventually lead to an arrangement of spheres that formed a model for the solar system and planets. Unfortunately for Kepler, no amount of study of possible arrangements of the perfect solids led to a satisfactory theory of the Heavens. Fortunately for us, he did not give up and started over with a new idea.

9.1 Kepler's Laws

Kepler's discovery of his laws stemmed from his willingness to give up the idea that that paths of the planets were circles. Instead, he chose to use an ellipse - a shape like an elongated circle. Kepler's basic model then was the original heliocentric model of Copernicus (Sec. 7) built with ellipses instead of circles.

Planet	Distance	Period	D-Cubed	P-Squared
Mercury	0.39	0.24	0.59	0.58
Venus	0.72	0.62	0.37	0.38
Earth	1.00	1.00	1.00	1.00
Mars	1.53	1.88	3.53	3.58
Jupiter	5.21	11.9	141	142
Saturn	9.55	29.5	871	870

Table 2: Table comparing Orbital Period (in years) to average distance from the Sun for the five planets known to Kepler. The columns with the square of the period and cube of the distance show how nearly this matches Kepler's third law.

Kepler produced three laws, one for the shape of the path follows by the planets, one giving the times that a planet would be at a particular point on its path and lastly, a law which predicted the decrease in speed of the different planets as one progressed further from the Sun.

First Law:(Sec. 9.2) The orbit of each planet is an ellipse with the Sun at one focus.

Second Law:(Sec. 9.3) The line joining the Sun and a planet sweeps over equal areas in equal times.

Third Law:(Sec. 9.4) The square of the periods of revolution of the planets is proportional to the cube of the average distance of the planet from the Sun.

9.2 Planets Travel in Elliptical Orbits

9.3 Equal Area Law Sets the Speed

9.4 Law 3 Gives the Length of Planet Year

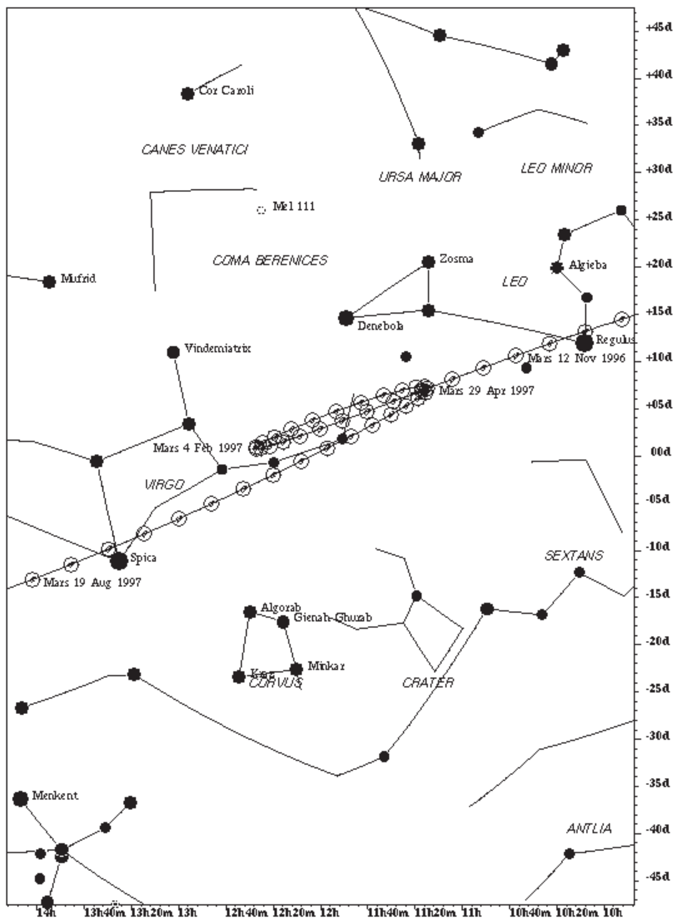


Figure 10: Retrograde Path of Mars

Figure 11: Aristotle's model of the heavens.

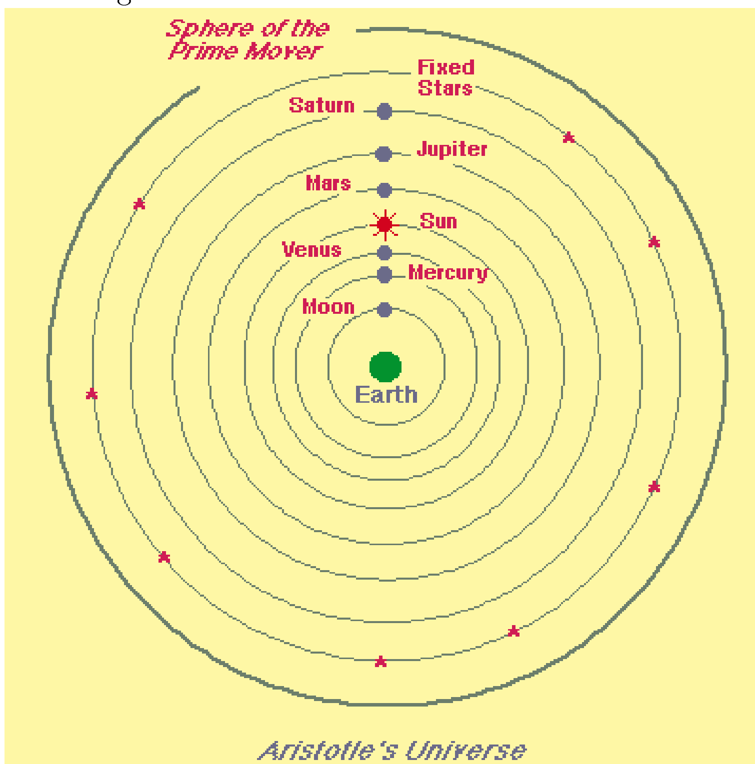


Figure 12: Epicycle: A circle on the circle carrying a planet

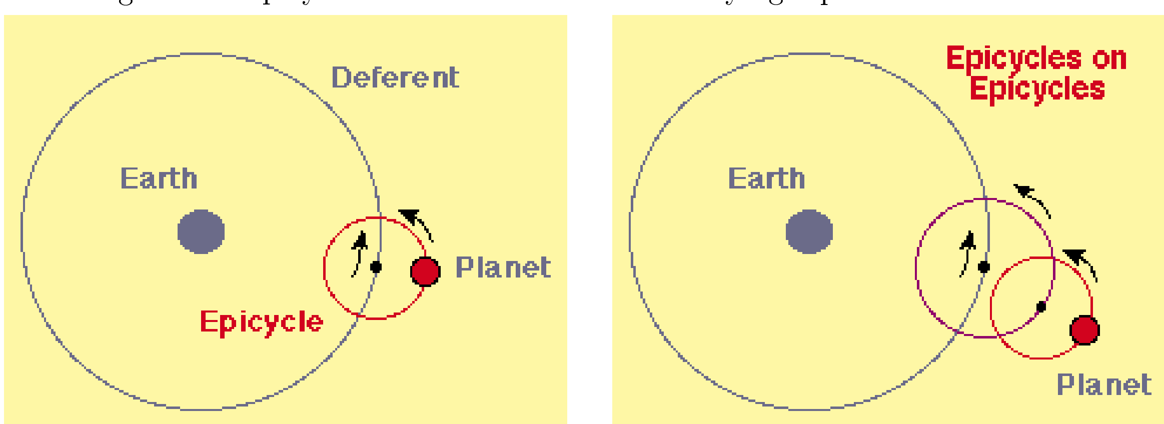


Figure 13: A view of the paths of Earth and Mars

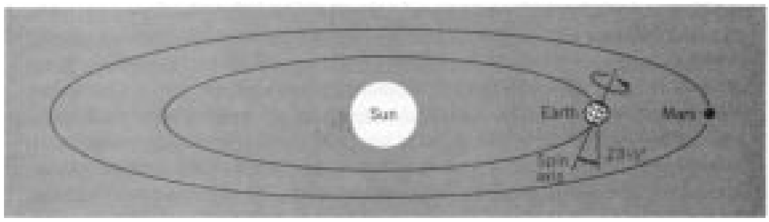


Figure 14: Diagram explaining retrograde motion.

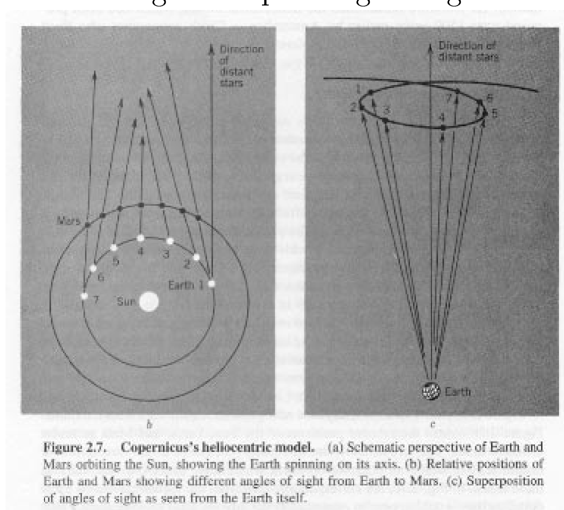


Figure 15: Nicolaus Copernicus, Feb. 19, 1473 - May 24, 1543 Born Torun, Poland, died Frauenburg, Poland.

Figure 16: Tycho Brahe (1570) Observational Astronomer

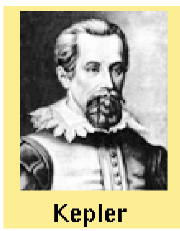


Figure 17: Johannes Kepler 1571-1630

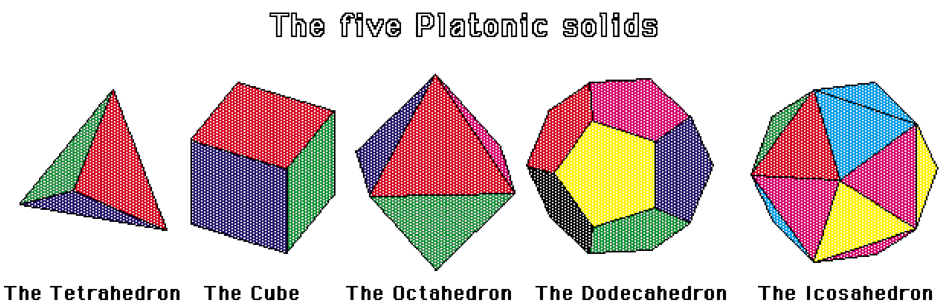


Figure 18: Platonic Solids used by Kepler in Mystic Model

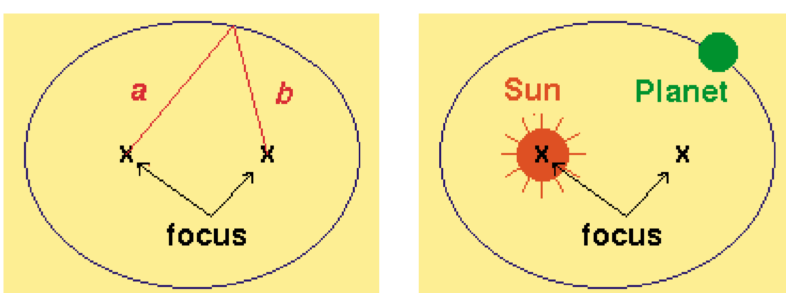


Figure 19: An ellipse has two foci

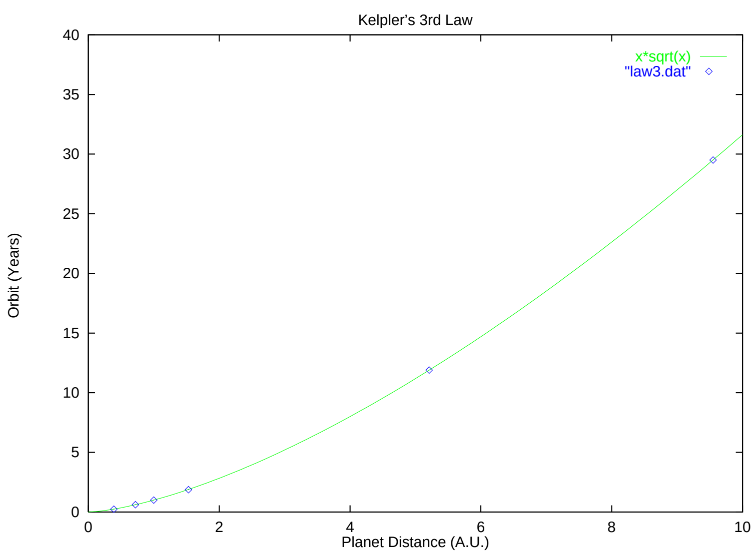


Figure 20: Data for Planet Period Compared to Law 3