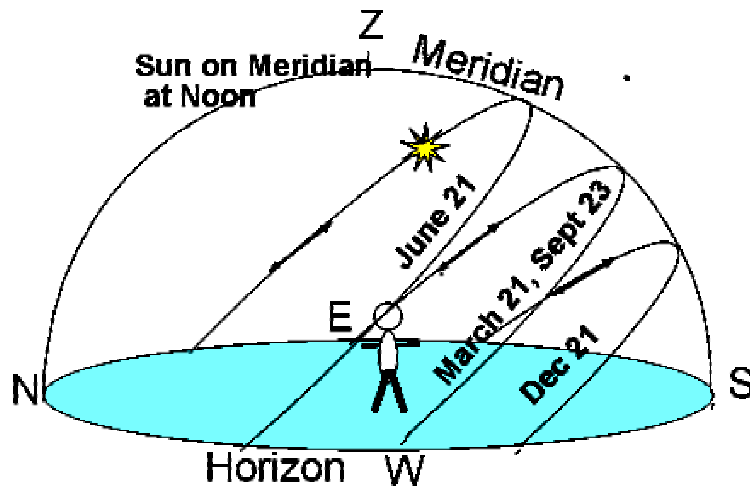


## Chapter 6 History of Astronomy-Ancient Times through Galileo

In this chapter we will be examining the way people's concept of the Universe has evolved. Some peoples have simply tried to predict what the sky would do and when it would do it. Others have tried to understand the Universe by making a model and comparing what we observe with the model's predictions. Comparing predictions from models with observations and experimental results is the way that science proceeds today.

There is a timeline at the back of this chapter. It includes several traditions of astronomy divided by geographic location. Many of these traditions were developed independently. Wherever people looked at the sky, they found a need to explain what they saw. Today's concepts have evolved from Mesopotamia through Greece to Europe.



**Paths of the Sun as seen from Northern Temperate Latitude  
Different Paths on Different Days of the Year**

What did they see? They saw everything that we can see today without a telescope. This list includes;

stars and planet rising and setting; changing points of sunrise and sunset, phases of the Moon, alignment of the Sun, Moon and planets compared with the stars, comets, eclipses. Let us follow the chronological development.

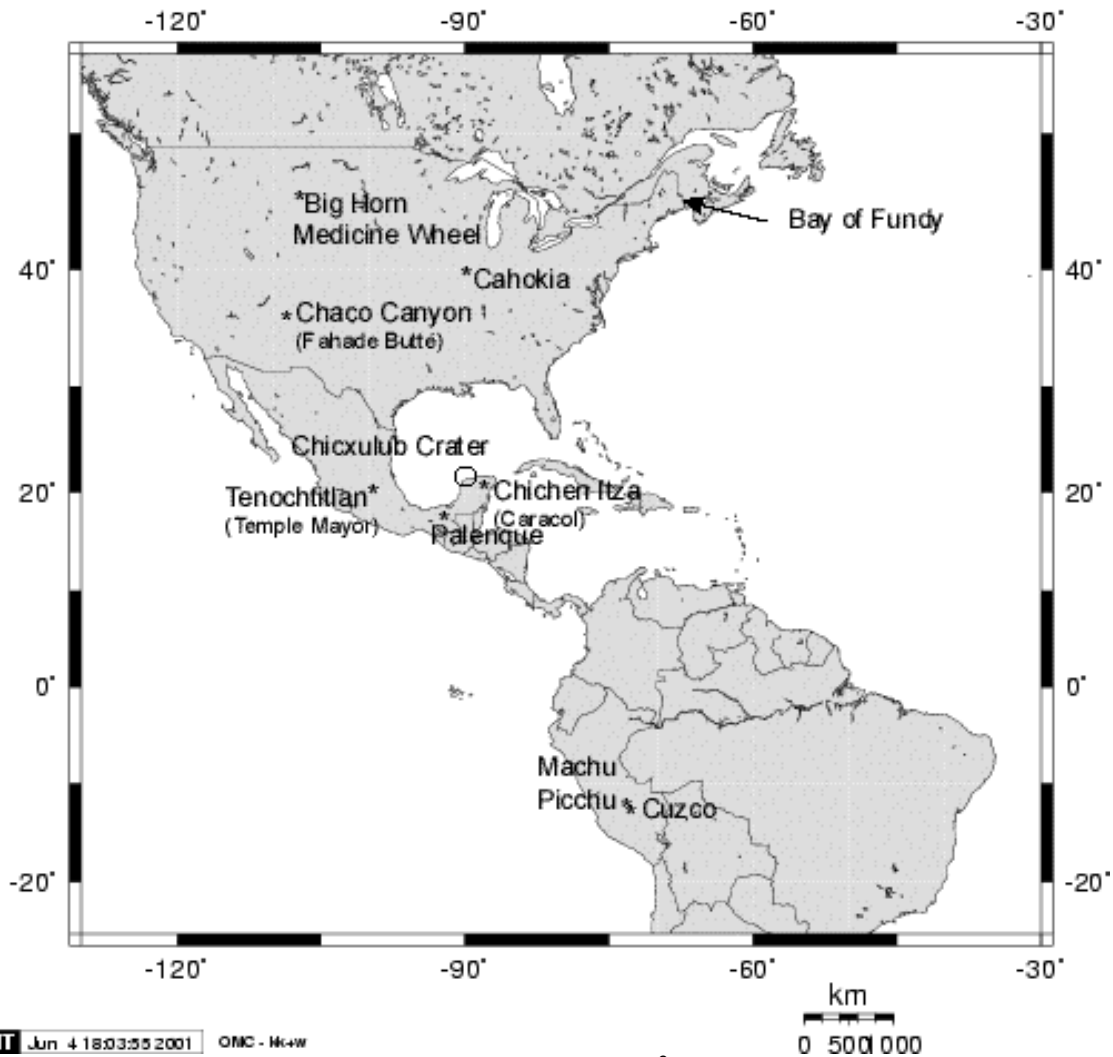
**Archeoastronomy is the study of astronomy without written records. The date archeoastronomy ended depends strongly on the culture involved. The Babylonians had cuneiform writing as early as 4500 BCE, while Hawaiians did not have writing when they were visited by Captain Cook in 1779 CE.**

Archeoastronomers often infer astronomical significance by finding parts of structures aligned with rising, setting, or (more rarely) meridian passage of the Sun, moon, planets or bright stars.

In the Great Plains (both the US and Canada), we have found ~50 structures called "Medicine Wheels". These are made of piles of stones laid on the ground in patterns with spokes and circles. Typical diameters of the Medicine Wheels are ~50 feet with heights of the rock piles of less than 2 feet. The number of spokes and circles in each varies, but alignments from one circle to another often indicate rising and setting points of bright stars, such as Sirius and Aldebaran. We don't know their purpose.

Further south, native Americans living in pueblos in Arizona and New Mexico used the position of sunset compared to distant hills to keep track of planting dates for corn. We have at least one case where these positions were explained to an outsider. Natives of the American southwest built many buildings with small windows aligned to specific sunrise and sunset dates, typically the solstice and equinox. e observer.

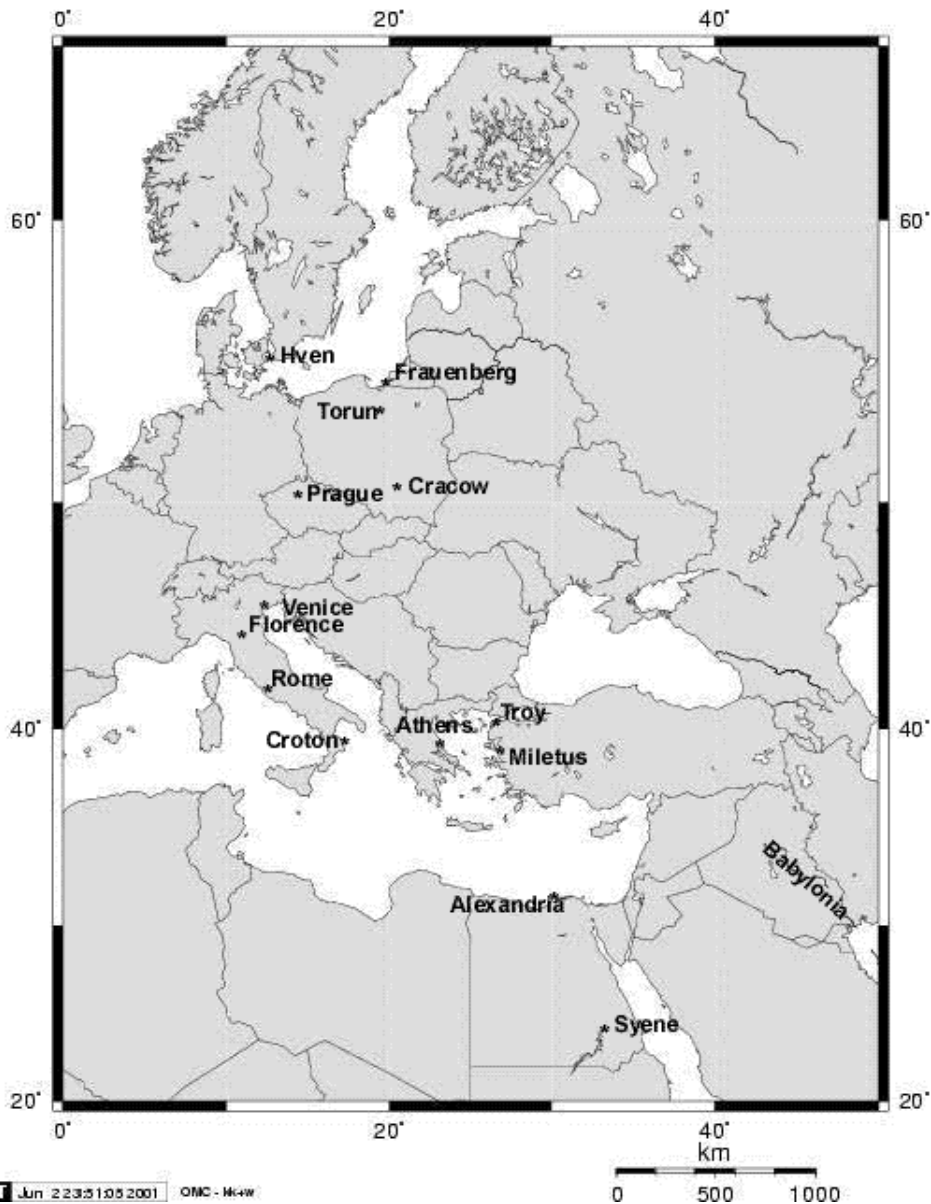
On Fahade Butte near Chaco Canyon New Mexico, we have found two spirals carved into rock. This is sometimes called the Sun Dagger because slabs of rock in front of the spirals cause daggers of light to cut down through the larger spiral at noon on the summer solstice, through the smaller spiral at noon on the equinox, and cause daggers to stay out of both spirals at winter spiral. The edge of the slabs of rock cause the shadow of the rising moon to fall in the middle of



the spiral at extreme northern moonrise (Moon at  $+28.5^\circ$  declination) and in the middle of the spiral at minimum extreme northern moonrise (Moon at  $+18.5^\circ$  declination). Fahade Butte is near Chaco Canyon, the site of Pueblo Bonito a great Kiva with hundreds of rooms. Chaco Canyon was a major trade and cultural center from about 1100 to 13000 CE.

Today's Mexico, Guatemala and Belize were home to a sequence of related cultures. The Olmec, Toltec, Mayan, and Aztec cultures seem to have evolved from one another. They built stepped temples and ceremonial cities with similar alignments. The Mayans, in particular predicted Venus' positions, eclipses and kept a cyclic calendar. They had writing and we are currently interpreting their writings. Some of their writings are carved into stone, others were painted on bark paper. Unfortunately, nearly all of the bark paper writings were burned by the settlers. Today only four Mayan codices written on bark paper survive. They were exported to Europe and not destroyed. The Dresden Codex, so named for the city where it is stored, includes tables of eclipses and of Venus positions.

In Britain, Ireland, and Brittany (northwestern France, near the English channel), people constructed passage graves, mounds, stone circles (made of worked stones set into the ground), and large combined constructions like Stonehenge prior to 2000BCE. There is evidence that these replace earlier, similar constructions, made of timbers. Statistical analyses of these constructions show some alignments to the solstice sunrise and sunset, and possibly some to the extreme north and south positions of the full moon rise and set. Over 1000 constructions are known today. Stonehenge, with a diameter of nearly 100 meters is one of the more impressive, though it has neither the largest diameter nor the largest single stone. Stonehenge was constructed in three stages, over a period of more than 1000 years, starting around 3000BCE. Some of its materials were brought from as far away as Wales.



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The tradition of astronomy leading to our present approach began with the Babylonians. The region they occupied is between the Tigris and Euphrates rivers, where Iran and Iraq are today.

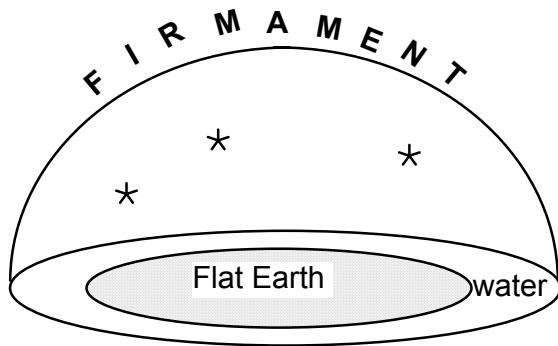
The earliest Babylonian writing probably dates to about 4500 BCE. They wrote using cuneiform, a combination of phonetic and ideogram representations was made of lines and triangles impressed into clay. The clay was dried and hundreds of thousands of examples remain today. The Babylonians named many of the constellations of the zodiac, the constellations along the ecliptic. They kept records of the motion of the Sun and the planets going through these constellations and created formulae predicting just where planets would be. We know because tables of the positions of Venus and Jupiter have been found, as have the formulas.

How long ago this activity started is less clear. The Babylonians kept dates in terms of number of years into the reign of each king. The problem is that we do not yet know the entire sequence of kings and the lengths of time that they reigned, so we don't know the dates for sure. Documentation of phases of the Moon and stars used to tell the time of day are found in a book called Enum Elish, which dates to around 1600 BCE. By the 700's BCE, regular observations of the planet's positions and of eclipses were made and recorded.

Babylonian astronomy stressed computing where things will appear in the sky. They used placeholders, like our 1's place and 10's place. But the Babylonians used 360 divisions for a circle and further divisions of 1/60 for each placeholder. This is where our current system of degrees, minutes, and seconds began. This system of numbers is much easier to use for computations than are the Greek (and Roman) number systems.

The Babylonians made careful observations and developed formulae predicting planet positions to support their astrological practices. The astrological predictions were considered so useful, that the observations and predictions continued even when the country was conquered.

The Babylonian view of the cosmos included a flat earth and roof like heavens called the firmament arching above. This model doesn't lead to mechanisms producing the observed motion of stars or planets. It is, however, very similar to the model underlying the Bible and is similar to some Egyptian and Greek ideas.



Babylonian Model of Cosmos

As the Babylonians continued their observations, civilization grew in the Greek mainland. The earliest indications we have of the state of Greek astronomy are in the Iliad and Odyssey. They include snippets of information such as that one should plant when the Pleiades rise at dawn. The Iliad and Odyssey were developed over hundreds of years, but dates for the completion of the text is usually somewhat after 1000BCE.

Hesiod's "Works and Days" (~ 850BCE)

includes a more formal type of star calendar called a **parapegma**. The parapegma associates the days of the year to plow, plant etc. with heliacal rising (rising right before the Sun, so that the body is just visible before daylight) of specific stars. Because of precession, the times of the year associated with these star risings are not now exactly at the same season.

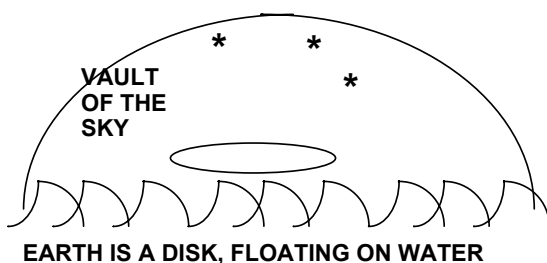
The Greeks got the idea to form theoretical models of the cosmos. Information about their concepts has come down to us, but we have none of the Greeks original writings prior to Plato,

Around 600 BCE, a trio of Greek expatriates (folks who left Greece) lived in Miletus, a former seaport in Asia Minor (today 8 miles inland in Turkey). They were the first to formulate theoretical models of the cosmos.

**Thales(624-547 BCE)**, the earliest of the Miletus astronomers, was reputed to have cornered the market on olives. He thought that water was the most important of the four elements (earth, air, fire, water). His model does not include any specific mechanisms to produce motions of the stars or the Sun or Moon. On the other hand there was an eclipse in 585 BCE, and Thales is said to have predicted it and frightened Miletus' enemies in a battle.

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**THALES OF MILETUS ( 624-547approx BCE) CONCEPT**



THALES BELIEVED:  
WATER IS THE FIRST PRINCIPLE, EVERYTHING ARISES FROM IT

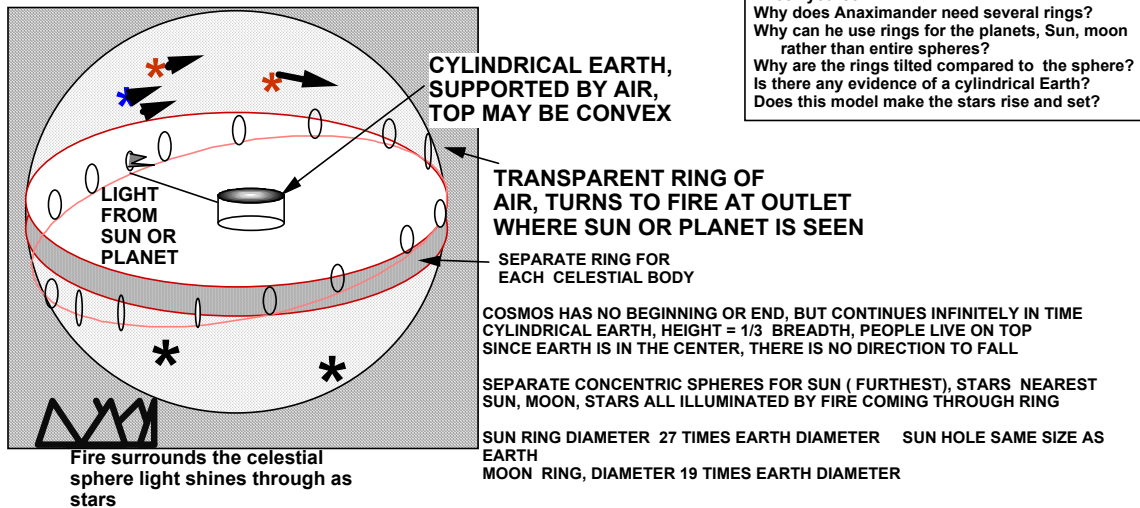
LATER AUTHORS CLAIM THALES KNEW SPHERICAL EARTH, ECLIPSES CAUSED BY SHADOW OF EARTH AND MOON, BUT INCONSISTENT WITH THIS MODE, BUT 585 ECLIPSE MAY HAVE BEEN PREDICTED FROM BABYLONIAN HISTORICAL DATA

Check yourself  
What does Thales model explain?  
Rising and setting?  
Motions of the planets?

Anaximander's model is striking because it uses an entire sphere of stars. The star sphere (Primum Mobile) causes the stars to rise and set while Earth stands still. He thought that the surface of the Earth is the horizontal part of a cylinder. He modeled the stars as holes in the Celestial Sphere, illuminated by fire surrounding the sphere. He modeled the motions of the planets, the Sun and the moon as imagining them carried by tilted rings. His tilted rings are similar to the observed paths of the planets, tilted compared to the celestial equator. The source of light for the Sun, Moon, and planets was compressed air, iwithn the tilted ring. The compressed air exits by a hole where it burst into fire, becoming visible. This model is meant to have no beginning or end in time, but to be perfectly regular and repeatable. Perhaps this was a reaction against the unpredictable mythological Greek gods.

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**ANAXIMANDER, MILETUS ( 611-546 aprox BCE)**



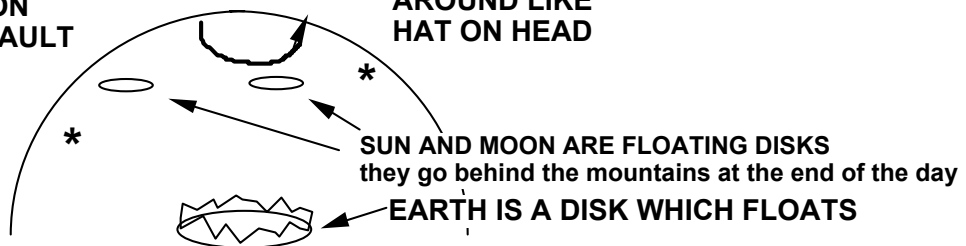
Anaximenes model, although later in time than Anaximander's is simpler and predicts less.

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**ANAXIMENES OF MILETUS ( 585-526 BCE)**

**STARS ARE FIXED LIKE NAILHEADS ON CELESTIAL VAULT**

**SKY ROTATES AROUND LIKE HAT ON HEAD**

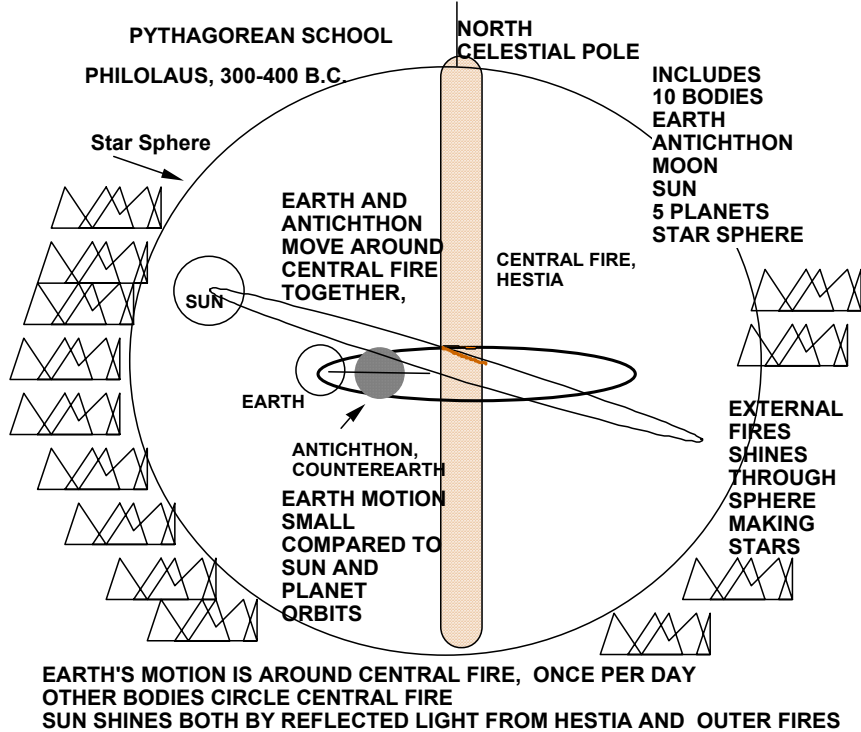


**Pythagoras (500-570 BCE)** lived nearly contemporaneously. He moved to Croton (~540 BCE), on the instep of Italy and founded a school and religion. It was a religion with secrets, mathematical secrets. Because of the secrecy, we do not know exactly what Pythagoras discovered and what was discovered by others later.

**Pythagoras** is thought to have discovered the relation between the squares of the sides of a right triangle and the square of the hypotenuse ( $c^2=a^2+b^2$ ). He also discovered that the value of  $\sqrt{2}$  is an irrational number. That means it cannot be represented exactly by a fraction. At that time the Greeks thought that every number could be represented exactly by the fraction. So they did not welcome the discovery of a value which did not fit in their worldview.

The Pythagoreans thought that the planets were small bodies carried on spheres centered on the spherical Earth. They thought that the sizes of the planets' spheres were not arbitrary. Rather they were determined by the relations between the notes of musical chords. If one were to listen (and realize that the ever-present background was the music), one would be able to hear the "Music of the Spheres".

At least one of their models, attributed to Philolaus, hypothesized that the Earth was not exactly at the center of the Universe. Rather the model treats the Earth as moving around a central spindle of fire every day. When we face the Sun, it is daytime. When we face away, it is night. The Sun shines by reflected light from Hestia. We, Earthlings, don't see the spindle of fire because the counter earth, called the Antichthon, stands between Earth and the fire. The system includes 10 bodies total, including the Sun, Moon, Earth, planets, Antichthon, and spindle of fire.

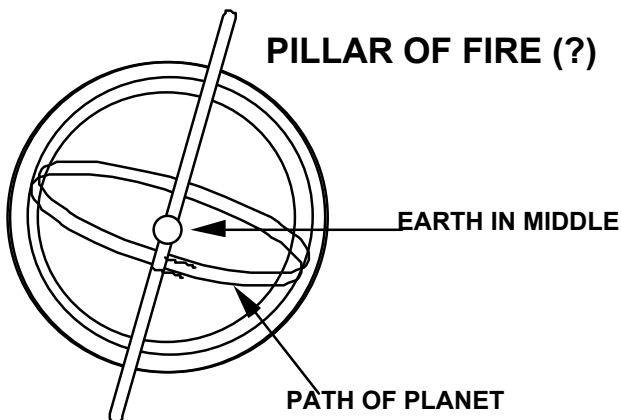


**BASIS FOR PLATO'S MODEL**

**Plato (427-347 BCE)** is the first of the Greeks whose writings we have today. Plato was primarily a philosopher. He thought it was not worthwhile to make observations, because only external features can be detected. But Plato was interested in the true nature of things, which he thought would never be discovered in this way. On the other hand, Plato was aware of the Pythagoreans and probably knew about Philolaus' model.

Plato didn't write any astronomy book. On the other hand, he described the natural world in parts

of his "Dialogues" and "Timaeus". They were written about 20 years apart, so it is possible that his opinion changed between the times of writing. Timaeus includes a long discussion by a person who is identified as a Pythagorean. Whether Plato actually wrote Timaeus is highly questionable.



Plato had the idea that the part of the Earth known to the Greeks (the Mediterranean) was just a small part of

the Earth and there might be other civilizations on the Earth, of which the Greeks were unaware. (Was he correct?)

In Timaeus, a Pythagorean (NOT Plato) describes the physical universe as rotating around a central “spindle of fire” which keeps it together. The planets move on concentric spheres or “lips” or “rims” with the stars on the most distant rim. The rim where the stars are mounted moved the opposite direction to the motions of the other bodies (Sun, Moon and planets). This is to make the entire sky rise and set (apparent westward motion) while the planets and Sun moves eastward against the star background. Plato seems to have known about Philolaus’ idea that the Earth was not exactly at the center of the Universe, but rejected the idea.

DISTANCES CHOSEN FROM 2 SEQUENCES (Plato)	
MOON	1
SUN	2
VENUS	3
MERCURY	4
MARS	8
JUPITER	9
SATURN	27

Plato assigns a distance order to the planets, based on the times they take to complete their path through the sky. He assigns two series of numbers to their distances. 1-2-4-8 and 1-3-9-27. These sequences do not correspond to either the actual distances or the actual times to move along the ecliptic.

The impression of later workers is that Plato and/or Aristotle were convinced that any valid model of the universe must have the Earth at (near) the center (see Aristotle for why). They did not

distinguish the Sun or Moon as being very different from among the other bodies, but all the bodies were expected to **move in circles at constant speed around the Earth, which stands still at the center**. It is not clear that either Plato or Aristotle ever wrote this exactly, but later workers tried to make models with the Earth at the center and only circular motion.

**Aristotle (384-322 BCE)** was Plato’s student, but unlike Plato, he did believe that science was important and wrote many books about science. Aristotle generally believed that it was worthwhile to observe the physical world, to find out what it would do naturally. He did not set up controlled experiments (but that would have subjected the situation to an unnatural situation).

**Aristotle** had the idea that the world is made of Earth, Air, Fire, and Water. He distinguished between areas below the Moon, where things can change and the unchanging world of the heavens starting at the Moon and going further out. The Earth is composed of heavy things (earth and air) which sink to their natural places as close as possible to the center of the Earth. The heavens consist of air and fire which both float upward. He did not believe that there is any empty space. Wherever there was no obvious material, he thought that space was filled with ether (not the same as the anesthetic). Aristotle tried to find the nature of things. To do that, he observed them, but did not try to do experiments or control their behavior.

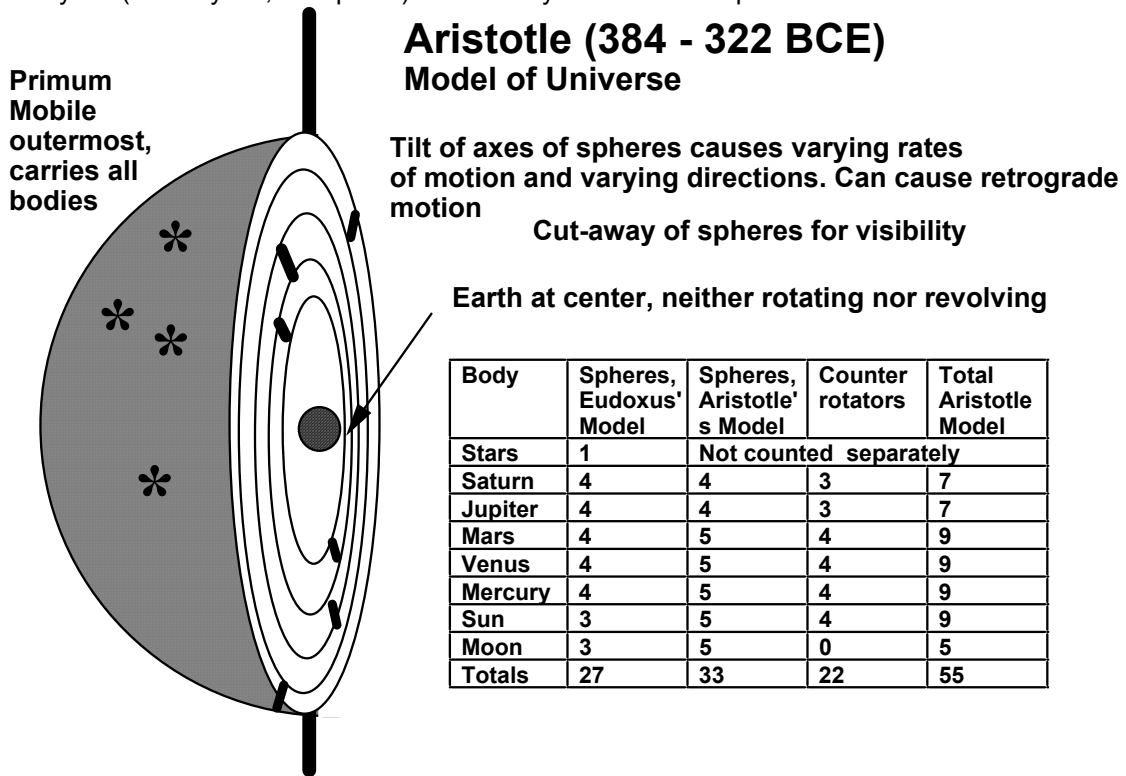
Aristotle, and his predecessor Eudoxus, tried to describe all of the motions of the heavenly bodies. Speaking generally, they and all the ancients tried explain the following motions:

- a) Rising and Setting of Sun, Moon and planets
- b) Sun, Moon and planets moving eastward among the stars, completing their paths around the sky in times from 27.3 days for the Moon, to 29.42 years for Saturn (slower than the rise and set)
- c) Planets moving retrograde when opposite the Sun or when at inferior conjunction (between Sun and Earth)
- d) Sun, Moon, and planets moving eastward with varying speed at specific repeatable parts of the sky (as measured by the position relative to the constellations of the zodiac)

Formulating a model to predict the apparent positions of the heavenly bodies occupied astronomers for nearly the entire next 2000 years. Aristotle thought of physical objects to make the motions occur. He did not believe that there could be empty spaces. Other astronomers were more satisfied with purely mathematical models to predict the positions.

Most ancient astronomers, including Aristotle, thought that the heavens were moved by a star sphere called the Primum Mobile (meaning prime mover). The purpose of the Primum Mobile is both to get everything moving and to cause rising and setting. Every day (23 hours 56 minutes) the star sphere moves WESTWARD around the stationary earth dragging all the other objects with it. The Primum Mobile was considered so basic, that most authors do not even mention it.

Eudoxus realized that combinations of circular motion with different axes can produce retrograde motion as seen by the Earth at the center. Eudoxus thought of a model using 27 spheres to carry the 5 planets, the Sun, and the Moon around the Earth. Aristotle built on this model, and expanded it to 55 spheres plus the Primum Mobile. The planets, Sun, and Moon were envisioned as small things fixed to the spheres. Aristotle thought that spheres would spin forever, so there would be no problem in keeping the bodies moving. Aristotle envisioned the spheres being made of crystal (rock crystal, like quartz) so that they would be transparent.

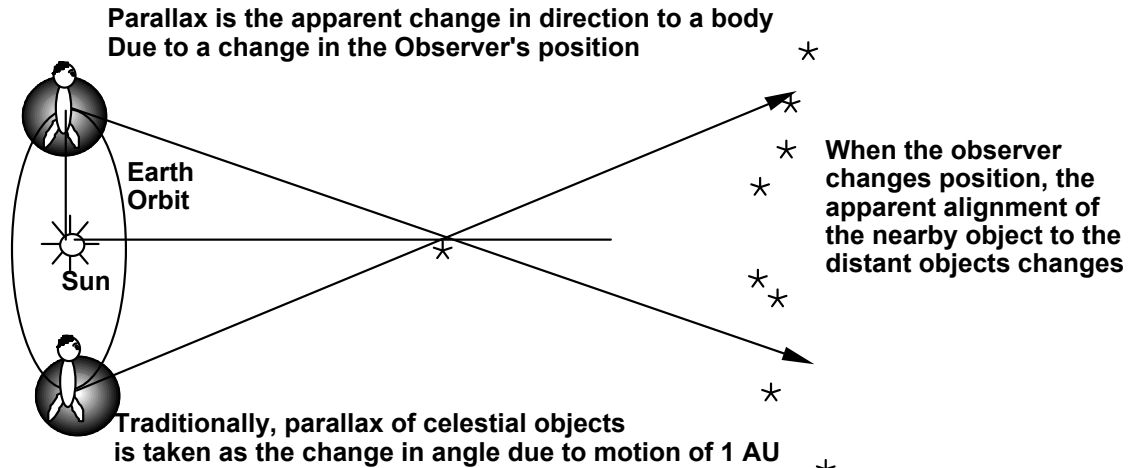


It may seem awkward to have everything move around the Earth, rather than assuming that the Earth spins. Until telescopes were in use (1600's CE), there was no reason for people to believe that the planets were anything but little lights. So it was far easier to move them than to move the heavy Earth. In the 200's BCE. Aristarchus figured out the distances to the Sun and the Moon. The combination of their distances and their appearance indicate that the Sun and Moon are large. This may have been what led Aristarchus to believe that the Earth orbits the Sun.

Most people thought that the Earth could not be moving because

- we cannot feel it move
- we would fall off if the Earth were moving
- if the Earth moved, we would notice that we get closer to the stars on one side of the sky for part of the year, but we don't
- if the Earth moved, we would see parallax, but we don't
- besides, the Universe is made for mankind, so why would the Earth move

## Parallax Due to Earth's Orbit



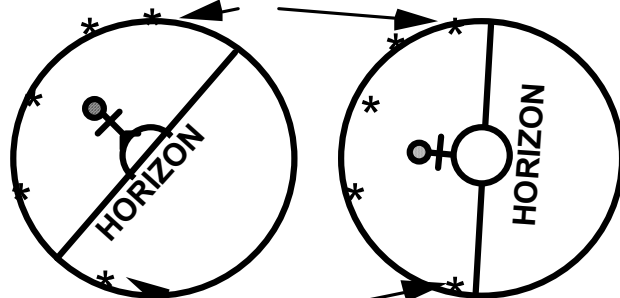
So all of these arguments combined to make most folks (including Aristotle) believe that the Earth did not move. Why didn't the stars look different on the different sides of the orbit? And why didn't they observe parallax as the Earth moves around the Sun? These effects are far smaller than people expected and are very hard to see. It actually took until 1838 CE for anyone to see parallax of any star. Then they picked a nearby star and lined themselves up with a chimney to keep things straight.

The very largest parallax angle of any of the stars, is about 1/5000 degree. So it is understandable why ancient people did not observe parallax of the stars.

Aristotle believed that the Earth is at the center of the Universe and does not move. He reasoned that if the Earth moved, we would see parallax of the stars and the distances between the stars would appear smaller on the side of the sky that Earth is closer to.

Aristotle and other Greeks reasoned that Earth must be spherical due to the following observations.

### STAR FURTHER FROM HORIZON AT HIGHER LATITUDES



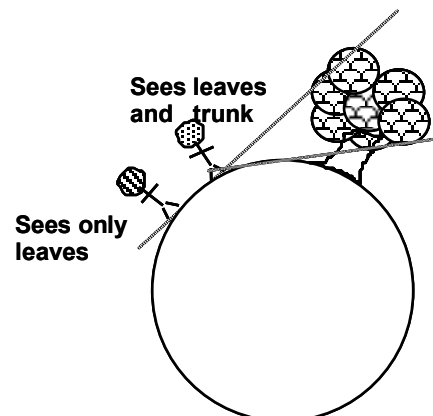
### STAR, NOT SEEN AT HIGHER LATITUDES

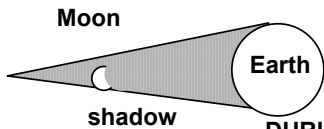
of the Earth. On a flat Earth, things would just fade into the mist.

During lunar eclipse, the Moon goes into the shadow of the Earth and the curvature of the shadow can be seen. Regardless of what part of the Earth faces the Sun and of the declination of the Moon, the curvature of the shadow is the same. If the Earth were any shape other than spherical, the shadow would have a different curvature at least some of the time.

First, different stars are seen at different latitudes on the curved earth. If the Earth were flat, the same stars would be seen.

Second, you leave an object it appears to disappear from the bottom up, due to the curvature





**DURING LUNAR ECLIPSE,  
SHADOW OF THE EARTH IS ALWAYS ROUND,  
ALWAYS CURVED THE SAME  
ONLY TRUE IF THE EARTH IS A SPHERE**



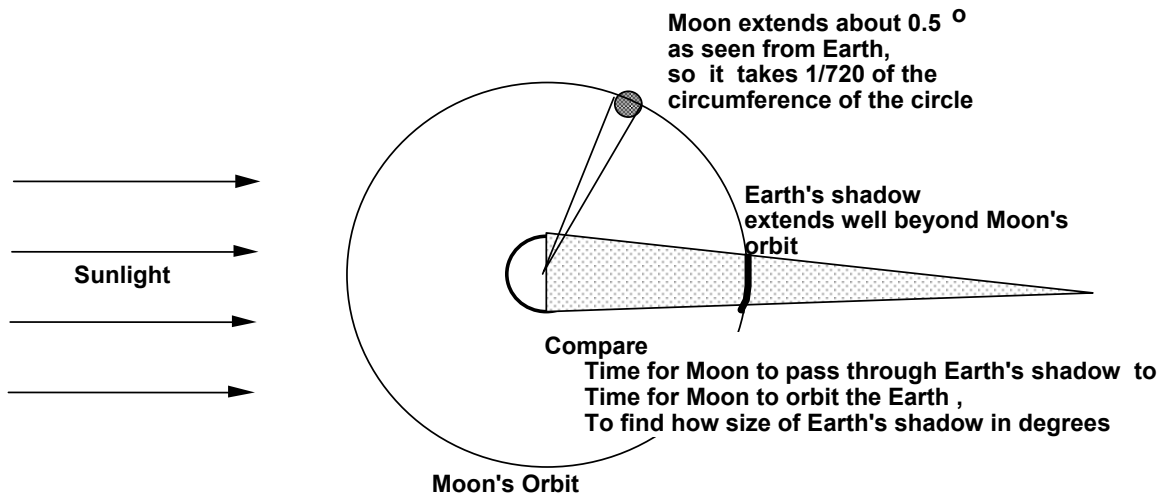
Aristotle wrote many of his ideas in a book called Physics. It was lost to Western Europe during the Dark and Middle Ages, but was retained by Islamic astronomers. When it was later translated to Latin, it became the standard in Europe until after 1600CE. Renaissance professors were required to teach their students how to interpret it. Aristotle's ideas included the following.

- Heavy things fall faster than light ones
- It is necessary to keep pushing on something (on Earth) to keep it from stopping
- When you shoot an arrow, the air keeps pushing the arrow to keep it going
- When the arrow is ready to fall, it just drops vertically
- Nothing beyond the Earth's atmosphere changes

Which of Aristotle's ideas is correct?

Aristotle was convinced that the Earth is at the center of the Universe, unmoving. But **Aristarchus (310-230 BCE)** believed that the Earth orbits the Sun. We do not have the book, or books which explain why Aristarchus thought the Earth moves. The idea was not accepted by other astronomers at the time.

We do have a book of Aristarchus' called "On the Distances to the Sun and Moon". In it he finds the sizes of and distances to both bodies using the methods below.



How did Aristarchus measure the distance to the Moon and its size?

When we look at the Moon (or the Sun) in the sky, we see that each of them is about  $1/2^\circ$  in diameter. Since we know that there are  $360^\circ$  in a circle, we can tell that the Moon takes up

$\frac{1/2^\circ}{360^\circ} = \frac{1}{720}$  of the circumference of Moon's orbit.. Aristarchus measured the time it takes the moon to move through the Earth's shadow during a lunar eclipse and compared that time to the time for the Moon to complete an orbit.. He formed the ratio

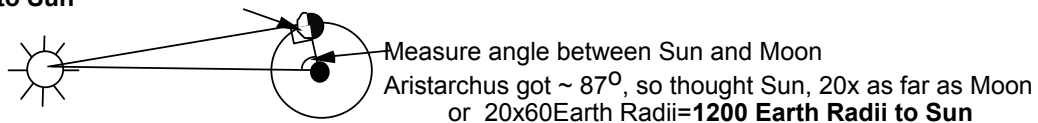
$$\frac{\text{Time for Moon to Cross Earth's Shadow}}{\text{Time for Moon to Orbit Earth}} = \frac{\text{Diameter of Earth's Shadow in degrees}}{\text{Circumference of Moon's Orbit, } 360^{\circ}}$$

Aristarchus knew the times for orbit and eclipse and he knew the  $360^{\circ}$ , so he solved for the Earth's shadow. He found that it takes up about  $2^{\circ}$  along the Moon's orbit. Since the Moon takes about  $1/2^{\circ}$ , the Moon is about  $1/4$  as large as the Earth. Not a small thing at all.

Using the fact that the circumference of a circle is  $2\pi R$  and the moon diameter (the  $1/2^{\circ}$ ) takes about  $1/720$  of this distance, we can find that the Earth diameter is about  $4/720$  or  $1/120$  of the distance to the Moon. We could say the Moon's distance is about 60 times the Earth's radius.

Aristarchus also measured the distance to the Sun in terms of the distance to the Moon. He got the idea that if he measured the angle between the Sun and Moon at the very moment when the Moon was either first or third quarter, he knew that the triangle with the Sun, the Moon and the Earth at each vertex would have a right angle ( $90^{\circ}$ ) at the center of the Moon. He measured the angle between the Sun and Moon as seen from the Earth.

#### Distance to Sun

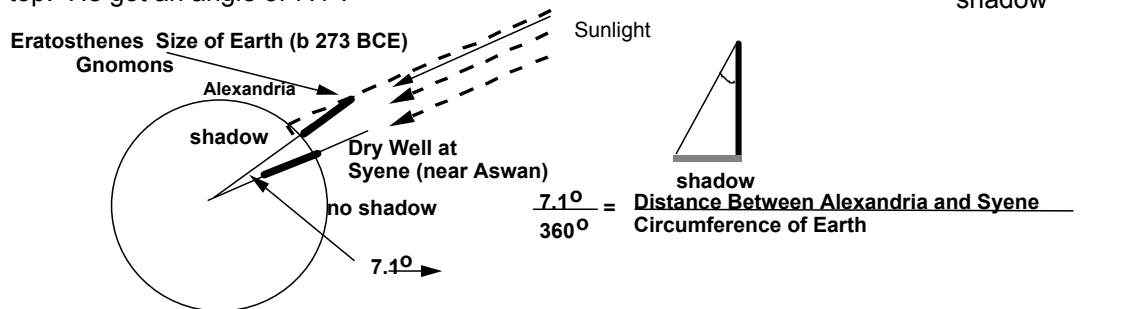


Aristarchus measurement, that the Sun is 1200 Earth Radii away, is impressive, but wrong. Interestingly, it was not challenged for at least 1800 years. The measurement was wrong because the angle at the Earth should not be  $87^{\circ}$  (leaving  $3^{\circ}$  for the angle at the Sun). The angle at the Earth should have been  $89 \frac{5}{6}^{\circ}$  leaving  $\frac{1}{6}^{\circ}$  for the angle at the Sun. The corrected measurement puts the sun 400 times as far as the Moon or  $400 \times 60 = 24,000$  times the Earth radius. Since the Sun appears to be  $1/2^{\circ}$  across, the great distance means that the Sun is far larger than the Earth or Moon. So from Aristarchus' point of view, it would have made sense to move the Earth rather than move the Sun and Moon.

Aristarchus did not know the size of the Earth. It took Eratosthenes to find it.

**Eratosthenes** had heard that at Syene, upriver on the Nile, the Sun is at the zenith at noon one day of the year. Eratosthenes lived at Alexandria, on the Mediterranean Sea, where he knew that the Sun never reaches the zenith. Eratosthenes believed in the spherical Earth, and he assumed that the sunlight comes in parallel rays. So he expected that the difference in the direction of the sunlight was due to the curve of the Earth.

He got the idea to measure the angle between the surface of the Earth at Alexandria and at Syene. Eratosthenes stuck a stick, called a gnomon, into the ground at Alexandria. Sunlight came in at an angle to the stick, causing a shadow. He measured the length of the stick and the length of the shadow. There was a  $90^{\circ}$  angle between the stick and the shadow. So he could complete the triangle and measure the angle at the top. He got an angle of  $7.1^{\circ}$ .



The angle between the stick and the sunlight is the same as the angle at the center of Earth with one end at Alexandria and the other at Syene. Eratosthenes knew that the ratio of the distance between Alexandria and Syene (the 5000 stades) to the Earth's circumference is the same as the ratio of the angle at the center of Earth to  $360^\circ$ .

We do not know the exact location of the gnomon at Alexandria. Neither do we know the exact size of the stade. So we do not know exactly how accurate Eratosthenes measurement was. Estimates are that it is accurate to within ~10%.

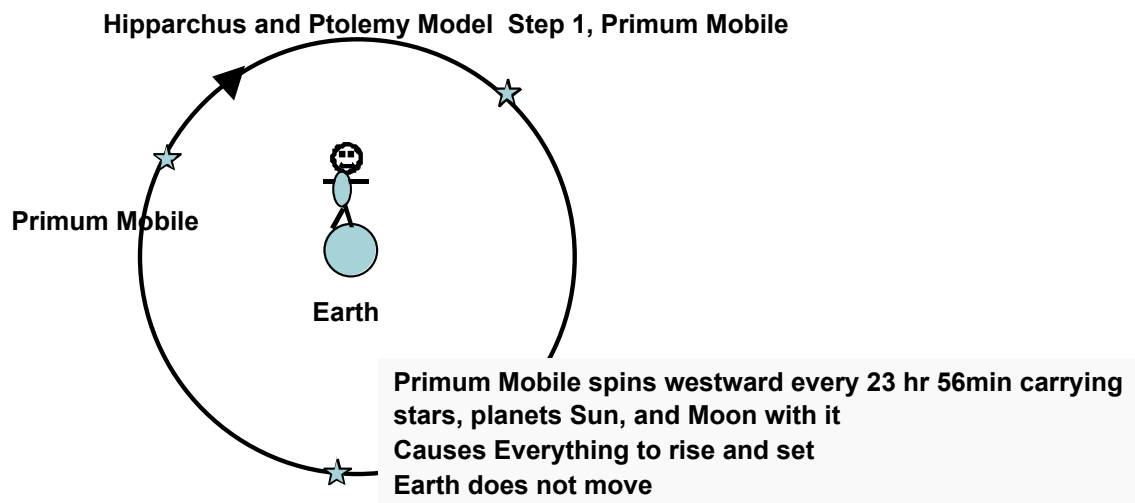
So by the 200's BCE, the Greeks had a good idea of the size of the Earth and the Moon. They know that the Earth was not nearly the largest part of the Universe.

Aristotle's model for planetary motions did not survive to modern times. The tilted, counter rotating spheres were replaced by a method to produce retrograde motion using **epicycles**, that is, circular motions on top of other circular motions. **Hipparchus (~150BCE)** developed this method, first discovered by Apollonius (~225 BCE) to model the Universe. Hipparchus also made the first star catalog to use the magnitude scale of star brightness and he realized that the position of the Sun at the Equinox was changing. This led Hipparchus to the discovery of precession.

### Hipparchus' and Ptolemy's Models

Both Hipparchus and Ptolemy used four separate features to explain the motions of the planets (and Sun and Moon) that they had observed. The model is explained, feature by feature below.

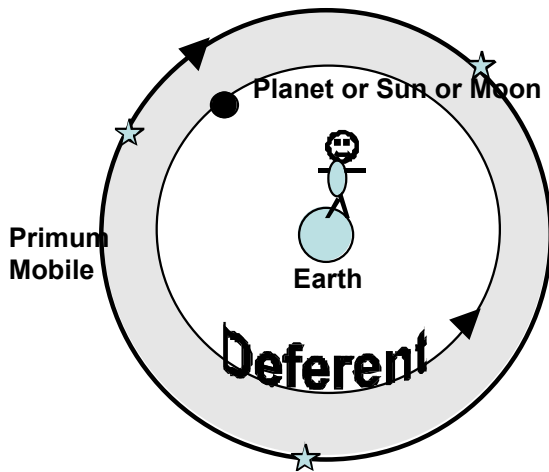
Hipparchus and Ptolemy (and Aristotle and earlier astronomers) used the **Primum Mobile** to cause all bodies to rise and set daily. All the celestial bodies were carried by the Primum Mobile. The separate motions of the planets, Sun and Moon were imposed on top of the motion of the Primum Mobile.



To envision the way that the Primum Mobile works, imagine a merry-go-round. In Hipparchus' and Ptolemy's view the Earth is in the middle not moving. This is like the merry-go-round operator standing in the middle **on** the ground, unmoving. The floor of the merry-go-round moves quite fast carrying everything on the ride past the operaor. The floor is like the Primum Mobile. As it goes

by, the horses and kids pass in and out of view, like rising and setting.

### Hipparchus and Ptolemy Model Step 2, Deferents



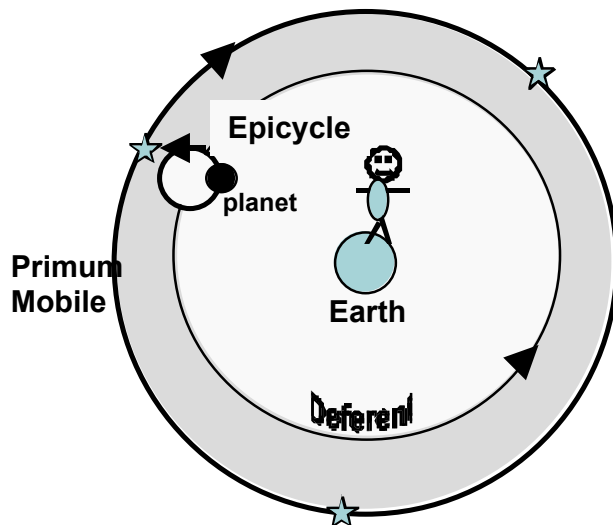
Each object, the Sun, Moon, each planet is carried by its own DEFERENT to move it east past the stars every year, month etc.

The Primum Mobile carries the deferents Westward causing rising and setting.

To model the motion of each body near the ecliptic, each body was given a separate path around the Earth, RELATIVE to the Primum Mobile. This path, called the **deferent**, carries the bodies eastward through the sky, near the ecliptic.

Continuing to compare the model to a merry-go-round, you are still the operator. Motion of the planets on the **deferent** is like the motion of people walking on the merry-go-round floor in the direction opposite to the spinning. The people go slowly compared to the floor. Each time the floor passes you (rising and setting), the people are at a little different position compared to the fixed horses and poles. Eventually the people go past every one of the horses and return to the same position. This is like each of the planets (or the Sun or Moon) completing its path along the ecliptic.

### Hipparchus and Ptolemy Model Step 3, Epicycles

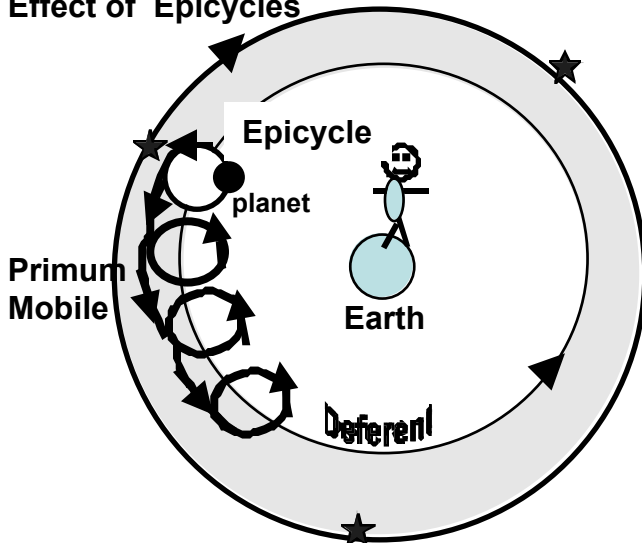


Each planet was given an epicycle to cause retrograde motion. The center of the epicycle is carried by the deferent and the planet is attached to the epicycle.

To make the body move retrograde, each body was modeled moving on an **epicycle**, on top of the deferent. So for Each body, Hipparchus defined the relative size and timing of the Primum Mobile, a deferent, and an epicycle.

Returning to the merry-go-round model, the epicycle is what would happen if the people walked in little circles as they walked along. Some of the time the person is moving backward part of the time, when compared to the horses etc (all the time the floor is causing the person rise and set).

**Hipparchus and Ptolemy Model Step 3, Effect of Epicycles**



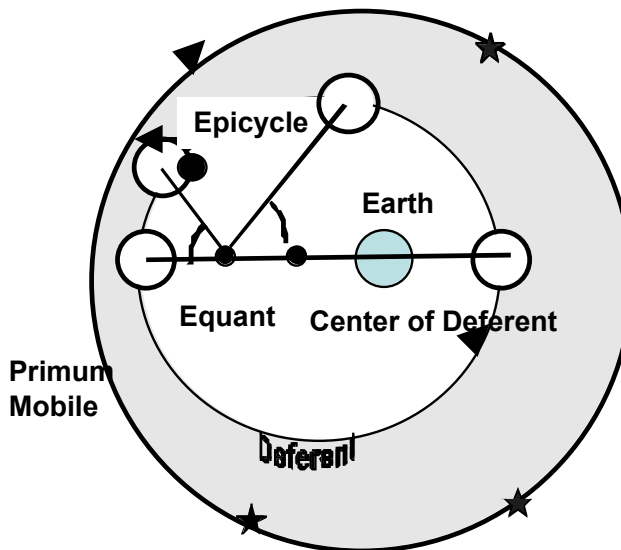
The epicycle model, with the Primium Mobile, an epicycle, and a deferent for each body produces rising and setting, motion of the planet eastward through the stars, and in regular retrograde loops. But each planet does not have the exactly the same retrograde motion every time. Hipparchus knew this and modeled the irregular speed and loop size by moving the deferents so the Earth was off-center (called eccentrics).

**Motion of Deferent and Epicycle Cause Loops Retrograde Motion when planet is closest to Earth**

astronomers, especially from the work of **Ptolemy (100-170 CE)**. Ptolemy's work has survived. Ptolemy's most famous work is the *Almagest*, a compendium of models using epicycles, a revised star catalog, revised estimates of the rate of precession, and information on how to use the computations for astrological purposes.

Hipparchus' writings have not survived. We know about his work from the work of other

**Hipparchus and Ptolemy Model Step 4a, Equant**

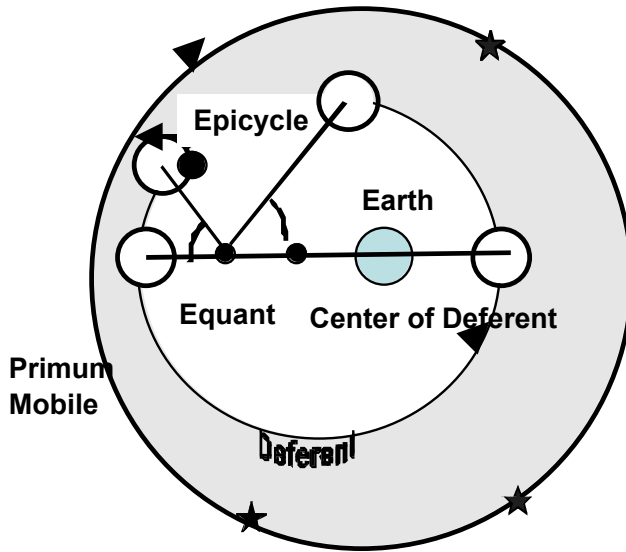


**Epicycles cause retrograde motion, but every loop would be the same, NOT what is observed.**

**Deferent pushed off-center from Earth. Equant, same distance from center as Earth, but opposite side. Apparent deferent motion same everywhere as seen from Equant.**

Ptolemy used the same kind of model as did Hipparchus for the Primium Mobile, the deferent, and the epicycle. He used **equants** to cause both the

### Hipparchus and Ptolemy Model Step 4a, Equant



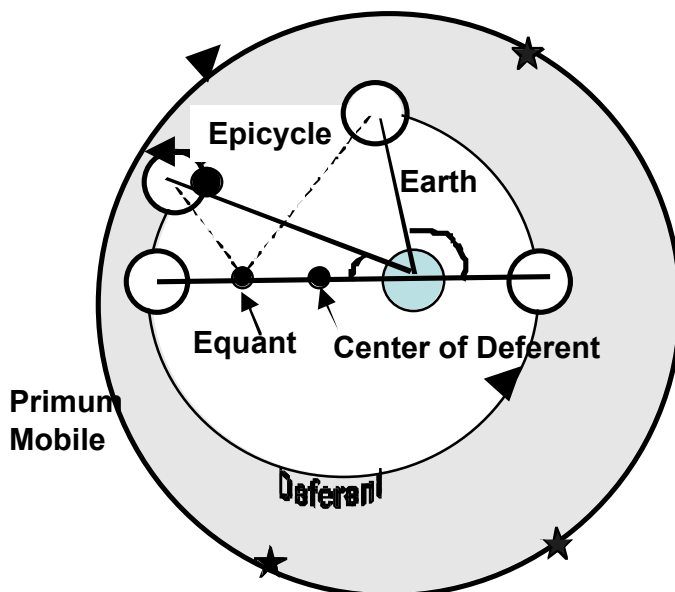
Epicycles cause retrograde motion, but every loop would be the same, NOT what is observed.

Deferent pushed off-center from Earth. Equant, same distance from center as Earth, but opposite side. Apparent deferent motion same everywhere as seen from Equant.

speed of motion through the stars and the size of the retrograde loops to vary. The Earth is to one side of the center and an imaginary point called the equant is at an equal distance on the other side.

The motion of the center of the epicycle on the deferent has an angular speed which appears to be constant from the equant. (The actual speed in space would not be constant.) Since the Earth is not at the equant, the speed of the center of the epicycle appears to change, going more slowly when the planet is further from the Earth and more rapidly when the planet is nearer the Earth.

### Hipparchus and Ptolemy Model Step 4b, Equant



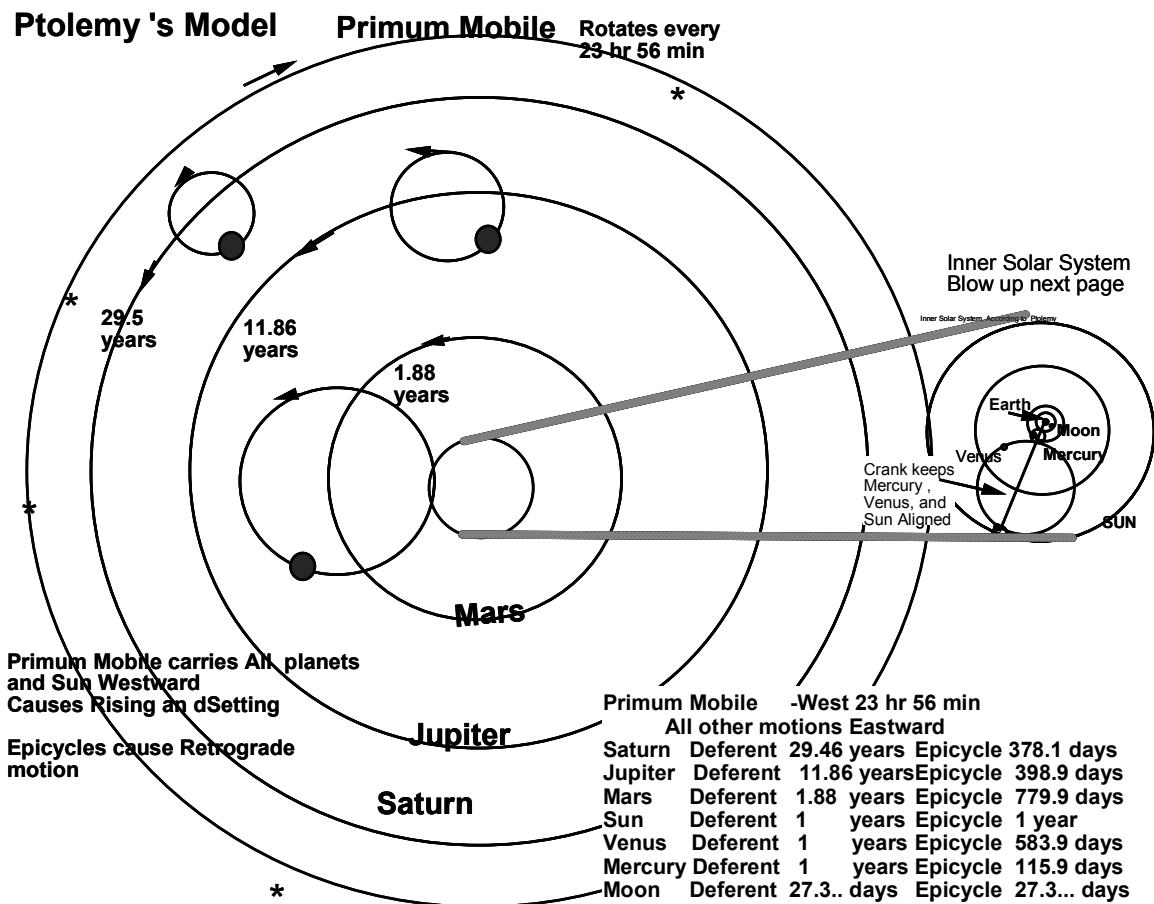
**As seen from Earth, the deferent moves  
Faster on one side of the Celestial Sphere**

Ptolemy understood that Mercury and Venus never appear at midnight. Instead they are roughly in the same direction as the Sun (to within about  $27^\circ$  for Mercury and to within  $46^\circ$  for Venus). To ensure this alignment, Ptolemy introduced a linkage between the Sun and each of these inner planets to ensure that they would stay in the same part of the sky. It is not clear whether he

believed the linkage to be a physical object, or just a mathematical concept. Ptolemy figured out the sizes, start times, and the speeds for the Primum Mobile, and the deferents, epicycles and equants for each of the planets and the Sun and Moon. He did not have any observational reason to decide the overall size of the orbits, so he made the orbits just large enough that the planets on their epicycles did not hit one another. He used Aristarchus' estimate for the Sun's distance. The relative size of the epicycle compared to the deferent is determined by the apparent size (the angle) of the retrograde motion in the sky.

To use Ptolemy's model one has the start time etc for each body, and can figure out the position for any time in the future by adding up the motion of the Primum Mobile, the deferent and the epicycle. The equant is used to find the position of the center of the epicycle. Ptolemy wrote out tables in his books to help astronomers use the model to predict positions with less work. Some of these tables are included in the Almagest and in a book called "Handy Tables".

After Ptolemy died, Western Europe did not produce much innovation in astronomy. The Romans did not promote new science; in fact, the closest to a scientist we know of are compilers of scientific knowledge. The last Roman emperor was deposed in 476CE and the museum and library at Alexandria were lost its last member near 400CE, leaving the west detached from many of the writings and works of the Greeks, including Ptolemy, Aristotle and Plato.

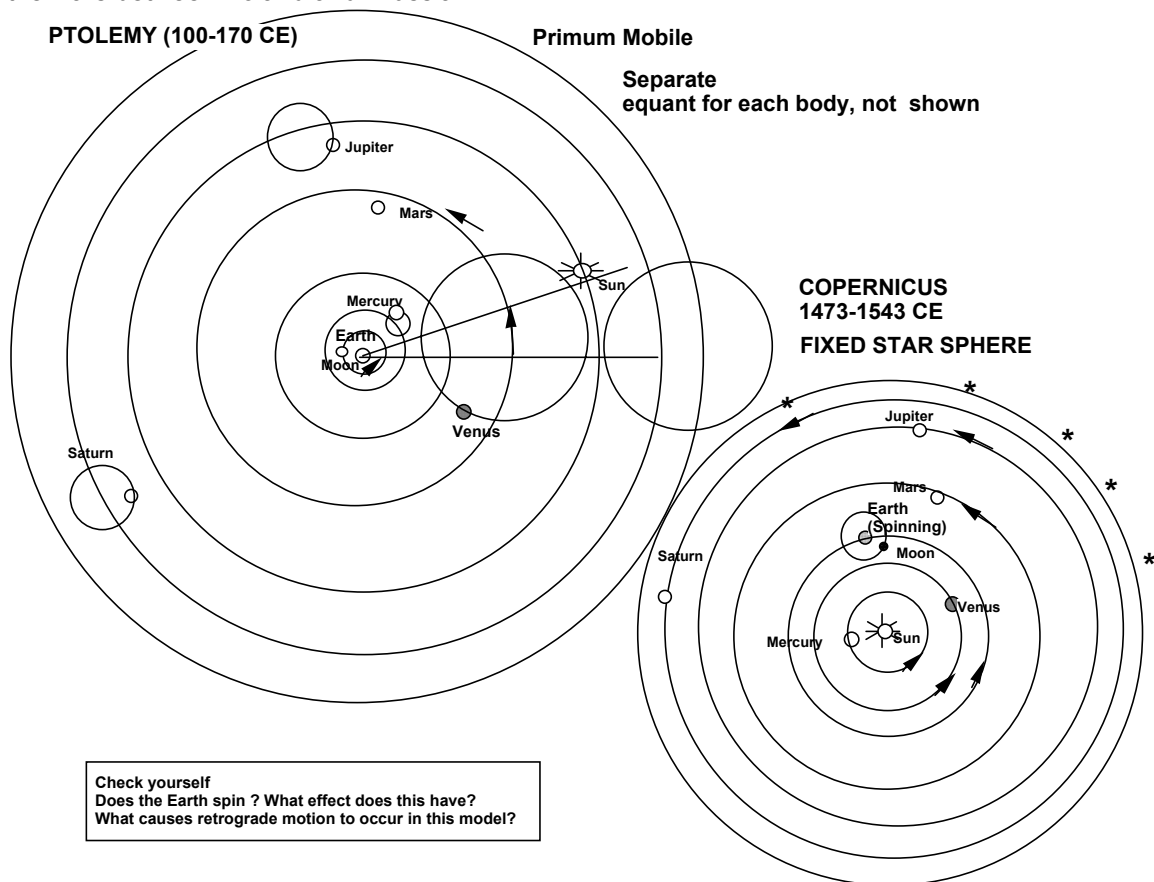


Astronomy was useful for finding the correct direction to Mecca (for prayer), for computing when the waxing crescent moon should first be visible to start the month, and for computing the time in the patient's horoscope to perform medical procedures. Ptolemy's models were used to make the predictions. In fact most of the star names we use today are Arabic names given by the Islamic

astronomers. The Islamic astronomers observed the stars and planets and compared their positions with the predictions. As the observed positions came to differ from the predictions in the Almagest, they made revised tables called zij's. The principals of prediction, the Primum Mobile, deferent, epicycle and equant were the same; the number values were different.

As Europe awoke from the Dark Ages, works of the Greeks were translated from Arabic into the Latin of the educated classes. Plato, Aristotle, and Ptolemy were taken as great authorities. Ptolemy's works were studied (and simplified to enhance understanding) and the tables were revised repeatedly.

Nicolas Copernicus (1473-1543) was born in Torun, Poland. He was educated at universities in Cracow, Bologna (canon law and astronomy), Padua (medicine), and got a degree in canon laws from the University at Ferrara. His uncle was Bishop of Ermeland. Copernicus was employed as secretary and physician to his uncle while the bishop was alive. He held the post of canon of Frauenberg cathedral for his entire life. After his uncle's death he continued at Frauenberg, acted as a consulting physician, studied astronomy, served in reforming the currency and negotiating in the wars between Poland and Prussia.



It is not certain when Copernicus got the idea of letting the stars stand still, and letting the Earth rotate (giving the impression of rising and setting) and having all the planets orbit the Sun. He was aware of Aristarchus' beliefs, but did not have Aristarchus' writings concerning the motion of the Earth. Copernicus was particularly disenchanted with the equant.

Copernicus wrote a brief summary of his theory, the Commentolarius (1510-1514?) and corresponded with other academics discussing his theory. During Copernicus' life even the Pope knew about the theory (1536). Copernicus was concerned because his theory conflicts with the Bible. His colleagues in the Church encouraged him to document his theories and predictions.

Their approach was that if the theory was correct, it would be reconciled with the Bible properly interpreted. Meanwhile it would be worthwhile to explore the theory and examine its correctness.

Copernicus delayed publishing his work. He was visited by Rheticus, a German mathematician, Rheticus. Rheticus was impressed by the theory, and with Copernicus' permission, wrote a brief summary of Copernicus' work. It was published and went into two printings. There were no negative repercussions. Copernicus was getting old, and he wrote up his life's work in a book called "**de Revolutionibus Orbium Coelestium (About the Revolutions of the Celestial Spheres)**". Copernicus completed the manuscript and sent it to Rheticus to prepare it for printing. Rheticus handed the work to Osiander, a Lutheran theologian.

Osiander (and Martin Luther) did not think that the world needed a theory of the universe separate from the information in Genesis. Osiander encouraged Copernicus to portray his model as just another way to compute the positions of the heavenly bodies, not an approach to finding the "truth" of the construction of the Universe. Copernicus did not take this advice, but Osiander wrote, and included, an unsigned preface to de Revolutionibus, expressing this very sentiment..

De Revolutionibus was published in the spring of 1543. Copernicus suffered a stroke in December of 1542, so he probably did not know of the preface. After Copernicus' death, his friends realized what had happened, but still the preface was not changed.

Copernicus' model of the Universe puts the center of the Earth's orbit at the center of the Universe. The Sun is near that point. The Earth spins on its axis and all the planets orbit the center of the Earth's orbit.. The orbits were circular with basically constant rate motion. Retrograde motion occurs as a natural consequence of the fact that the planets complete their orbits in differing lengths of time. As one planet passes another, observers both the inner and the outer planet see retrograde motion.

Copernicus knew, however, that the planets appear to change speed even when not in retrograde motion. Uniform speed motion on circular orbit will not make this happen. To model the changing speed, Copernicus introduced many small epicycles.

In Copernicus' model, the stars are assumed to be fixed on a sphere. Precession and changes in the amount of the tilt of the Earth are caused by changes in the direction of the Earth's axis.

Copernicus' model made it possible to determine the sizes of the planets' orbits in terms of the size of the Earth's orbit. Copernicus included sizes of the orbits in de Revolutionibus.

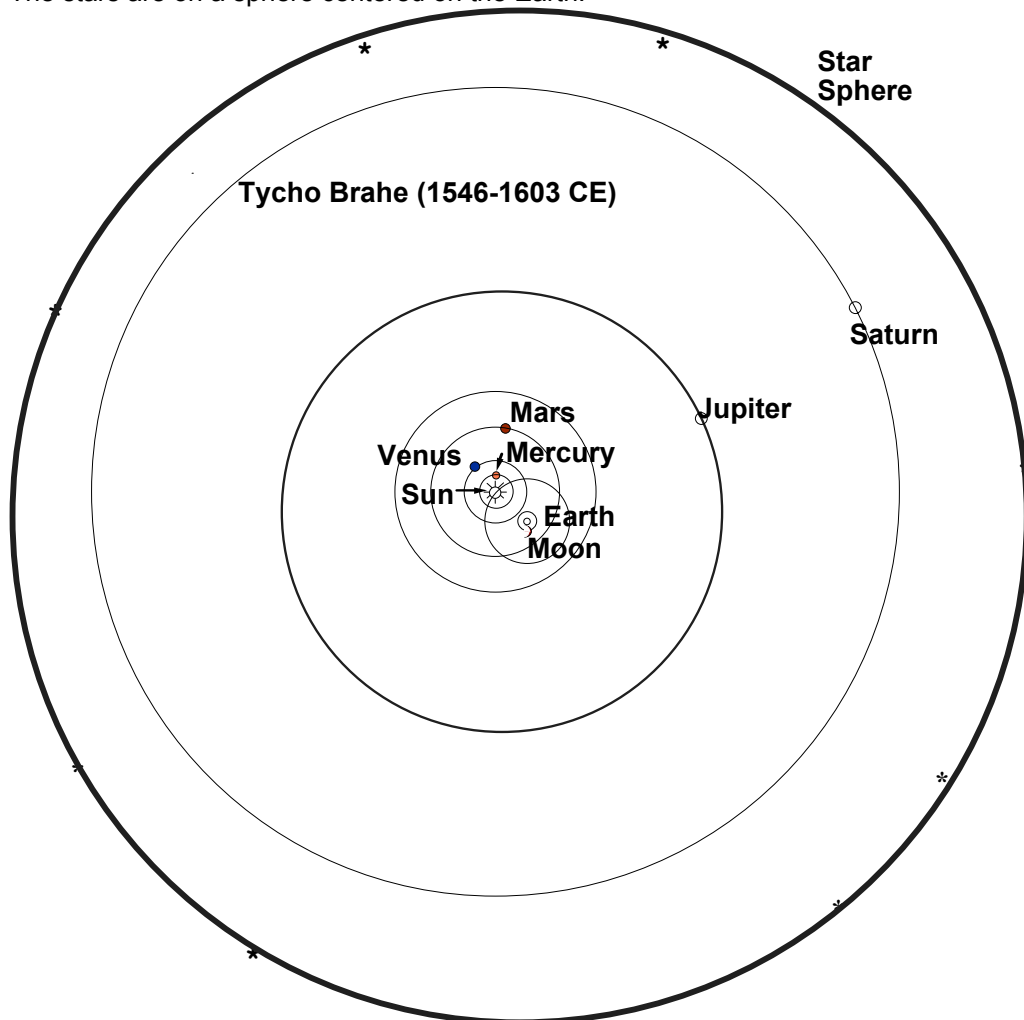
Copernicus made some observations to support his models and developed new computational devices to predict the positions of the planets. After Copernicus' death, these computations were used even by those who did not believe that his models were correct. At that time (and before) the astronomer's job was thought to be predicting the positions of celestial bodies. Explaining what lay behind the position computations was thought to be the realm of physics or philosophy.

Generally Copernicus' models were about as accurate as the Ptolemaic models, assuming that the Ptolemaic models were updated with new data. So most people did not believe that Copernicus was right. They were not anxious to demote the Earth from the center of the Universe to being just one among lots of planets. There was still the problem of conflict with the Bible. There was no good explanation of why parallax was not seen (Copernicus just said that the stars were too distant for parallax to be seen.). So few people accepted Copernicus model.

**Tycho Brahe (1546-1601)** was among the astronomers who did not accept Copernicus' model. He tried to measure parallax for stars, but could not find any. So he would not accept that the Earth moves.

On the other hand, Brahe did not accept Aristotle's contention that the heavens from the moon on out are unchanging. He found that comets could not be in the atmosphere (as Aristotle had said) because he could not measure any parallax. Since comets come and go, move among the stars etc. the heavens cannot be unchanging. Tycho observed a supernova in Cassiopeia, a star that brightened and faded. Both these phenomena change, but are not within the Earth's atmosphere.

Tycho Brahe was born a Dane. He observed the planetary positions at an early age and realized that the planets were not at the places predicted at the time predicted. So he thought he could make better predictions using his own model. His model has the Sun and the Moon orbit the Earth. The other planets orbit the Sun and are carried with the Sun as it moves around the Earth. The stars are on a sphere centered on the Earth.



Because he was Danish, and well known as a scientist, the Prince of Denmark lent him the island Hven in 1576. This island is near the coast of Sweden (and now is part of Sweden). The agreement was for Tycho to collect rent from the farmers on Hven to support himself, to carry on astronomical research (for the glory of Denmark) and to maintain the lighthouse.

Tycho Brahe moved to Hven and set up the first professional observatory in Europe. He built two separate buildings, Uraniborg and Stjerneborg to house his instruments and records. He built very large instruments allowing very accurate observations. Tycho was able to get observations precise to 1 minute of arc, that is 1/60 of a degree. Tycho hired helpers and they made observations for about 20 years. During that time the Prince of Denmark died and was succeeded by his son. The son was less interested in astronomy and less fond of Tycho Brahe. The farmers

were annoyed with the high rents and Tycho is reputed to have taken poor care of the lighthouse. In 1597 Tycho Brahe was forced to leave Hven. He settled briefly at Hamburg, then moved on.

Tycho found a new post as the Imperial Mathematician to Prince Rudolph of Prague (1599), so there he went. He brought many of the instruments for measuring the positions of the stars, since they were portable. (Obviously he didn't bring the buildings, and unfortunately they burned down shortly after Tycho left.)

Tycho made no more observations once he reached Prague. He tried to use the ones he had to develop tables to predict planet positions using his model. He hired helpers to make the tables. In 1600, he hired **Johannes Kepler** and set him to work on the planet Mars.

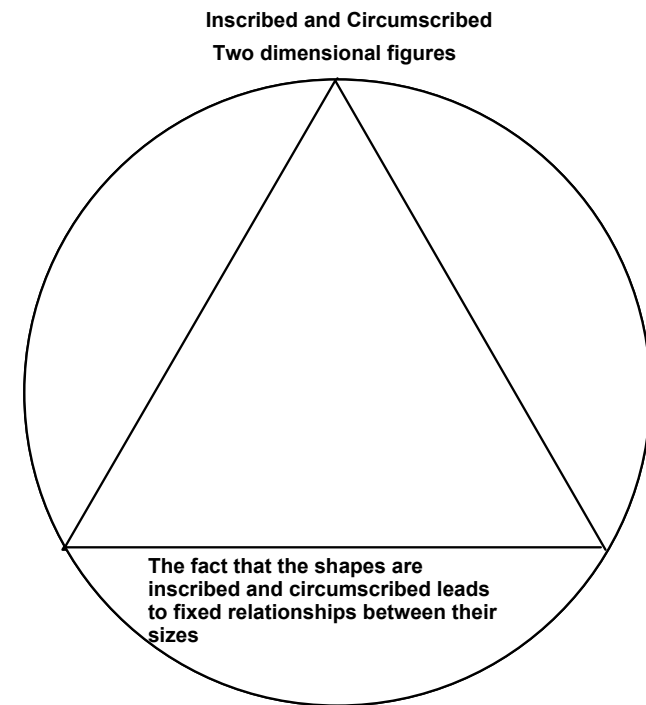
**Johannes Kepler (1571-1630)** was a German Lutheran. He originally wanted to be a clergyman, but was trained in mathematics and astronomy. One of the themes of his life was to find the meaning and structure in the universe. He obtained a job teaching, but his lectures were not attended.

Kepler noticed that that if the sizes of the planets' orbits in *de Revolutionibus* are represented by spheres, then the spheres could be fitted between the five known and possible three dimensional perfect solids. This is similar to two-dimensional inscribed and circumscribed polygons. The **perfect solids** have all of their faces the same and each edge of each face is the same. These solids had been known since the Greeks.

The **perfect solids** have all of their faces the same and each edge of each face is the same. These solids had been known since the Greeks. They consist of the tetrahedron (4 triangular faces), the cube (six square faces), the octahedron (8 equilateral triangles), the icosahedron (twelve pentagons), and the dodecahedron (20 equilateral triangles) There are only five such perfect solids in Euclidean geometry, and Kepler knew it.

Kepler reasoned that if the sizes of the planets' orbits in *de Revolutionibus* are represented by

spheres, then spheres of the sizes of the orbits for all six planets (Mercury, Venus, Earth, Mars, Jupiter, and Saturn) would fit with the perfect solids between them as spacers. Kepler thought that he had found the divine plan for the Universe; just 6 planets with spacing determined by the five (and only five) perfect solids.



Kepler published his theory in a book called *Mysterium Cosmographicum* (1597). He wasn't 100% happy with the values of the orbital sizes in *de Revolutionibus*. So Kepler sent a copy of *Mysterium Cosmographicum* to the man who had the world's best observations, Tycho Brahe. Kepler hoped that these observations would allow him to prove that the sizes of the planets' orbits fit with the perfect solids between them as spacers.

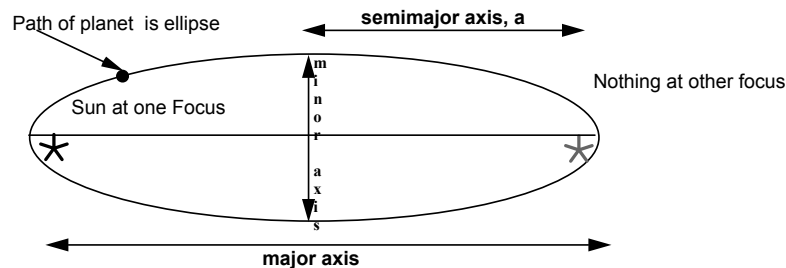
Fortunately Tycho Brahe, the man with the best observations, was looking for help. He hired Kepler to work on his observations expecting Kepler to prove Brahe's own model.

Kepler and Tycho Brahe did not get along. Brahe did not immediately give Kepler all of the observations he needed. Kepler got so frustrated that he went back to Germany once. In 1601 Tycho Brahe died and Kepler got possession of the observations. Kepler was given Brahe's job as Imperial Mathematician, but at a much lower salary than Brahe got.

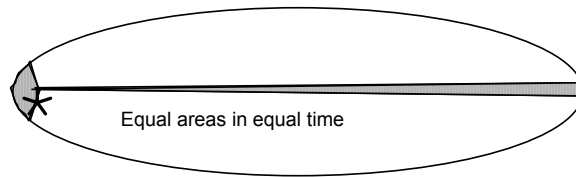
Kepler knew how accurate Brahe's observations were, so he could not simply assume that they were in error. He was forced to abandon the idea of circular motion, or motion carried on spheres and to adopt his three laws.

### Kepler's Laws of Planetary Motion

#### I. The planets orbits are ellipses with the Sun at one focus (known 1606, published 1609).



#### II The motion of the planets is such that a line from the planet to the Sun traces out equal areas in equal amounts of time (known 1606, published 1609).



#### III The periods of the orbits of the planets (P) to orbit the Sun are related to the semimajor axes of the orbits (a) such that $P^2 = a^3$ when the values are represented in units of years and astronomical units. (known 1616, published 1623)

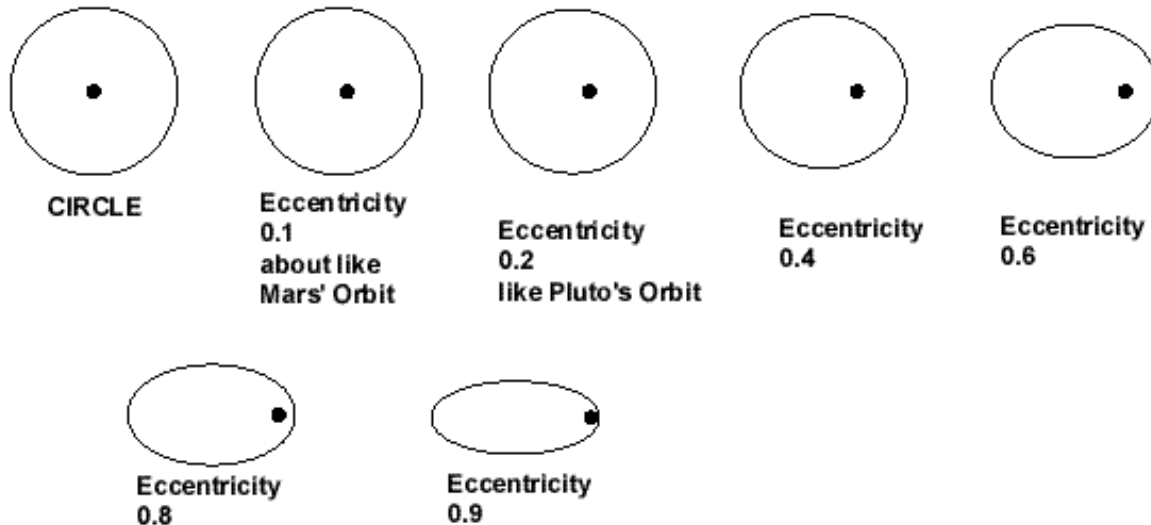
Ellipses are described by a formula involving the squares of the coordinates. You may have seen

it in the form  $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$ , where a is the semimajor axis and b is the semiminor axis. Ellipses

have two axes of symmetry. That means they can be folded along either the major or the minor axis and the sides will match (the fact that it would not matter if -x were substituted for x, or if -y were substituted for y, shows this symmetry). The shape of an ellipse is rounded everywhere; there are no straight parts and no points. The foci (the plural of focus) are on the major axis and at positions that depend on the shape of the ellipse.

The semimajor axis tells the overall size of an ellipse. In fact the semimajor axis is the average distance of one body from the other. It is like the radius of a circle.

Ellipses come in a variety of shapes, ranging from a circle to a very elongated shape nearer a cigar. The eccentricity tells how close to a circle it is, the larger the eccentricity, the more elongated the ellipse.) The orbits of the planets are very nearly circles. In fact, if it were not for the fact that the Sun is not at the center, it would be very hard to tell these ellipses from circles by just looking at the shapes.



Kepler did not really know why these laws were correct. The laws do, however give substantially more accurate prediction than did Copernicus' model. Today we know that these laws describe the motion of one body around another (laws 1 and 2) under the influence of gravity. The third law is appropriate for the motion of several small bodies around one more massive one, also under the influence of gravity. These laws could be derived from Newton's work.

Kepler was not persecuted for these laws, even though they do not have the Earth at the center. Probably this was because few people read or understood his work.

Kepler tried to explain why the planets orbit the Sun. The only force known at the time that acts without touching the other body was magnetic force (like when the refrigerator magnet tries to reach the refrigerator door before touching it). So Kepler tried to use magnetic attraction between the Sun and the planets to cause them to move in orbits.

Kepler used the models to develop tables, called the Rudolphine Tables, in honor of his (and Brahe's) patron Prince Rudolph of Prague. He went on to develop a new type of telescope (different from Galileo's), He learned that stars appear above further above the horizon than predicted, since their light is bent by Earth's atmosphere. And he computed many horoscopes. He still tried to find the overall plan of the Universe, later using musical harmonies rather than perfect solids.

**Galileo Galilei (1564-1642)** was a contemporary of Kepler's (they did not meet, but they did correspond). Galileo was a northern Italian, born to a musical family. Galileo had one brother and three sisters. His father sent him to university to become a physician so that he would earn money and be able to pay the sisters' dowries. The need to pay dowries may be what lead Galileo to put himself forward and seek favor at times when others would have been modest.

Galileo quickly decided that mathematics and astronomy were much more interesting than medicine and declined to become a physician. So he switched from the university at Pisa and went to Florence to study mathematics.

Galileo obtained a job teaching at Pisa after he finished university. Later he moved to Padua, the leading university of the day. He was supposed to teach Aristotle's physics and Ptolemy's models of the cosmos. Those were the accepted theories. Galileo performed experiments, however,

including measuring the time for various bodies to fall. He found that the time to fall did not depend on the mass of the body (but feathers and leaves still fall slowly. Why?). This led Galileo to conflicts with the scientific establishment.

Galileo discovered that a pendulum takes the same length of time to swing, regardless of how high it swings. You have probably experienced this when pushing someone in a swing. You push at the same time interval, regardless of how high they go. The time for the pendulum to swing depends only on the length of the string and the gravity of the Earth. Using this principle, Galileo devised an apparatus to time a patient's pulse.

Galileo spent many years studying the motion of falling bodies with their variable speed. Galileo slowed down the fall, to make it easier to measure, by rolling bodies down slopes. He found that bodies could roll to the same height they had come from. This is known as Galileo's law of inertia. He tried to describe the variation of speed that falling bodies undergo.

Galileo believed that Copernicus was correct and that the Earth moves. His reasoning was based on his personal theory of tides. Galileo thought that tides were caused by water sloshing around as it "turns the corner" from going the same direction due to both the Earth spinning and the Earth orbiting to the part of the Earth where it is moving opposite the direction that the Earth is orbiting. This model is NOT correct, but it motivated Galileo.

Galileo heard that in Holland, two lenses had been used together and with the result that the image was much magnified. He was living at Venice at the time, where there was (and is) a tradition of glass making. Galileo had many lenses made, and hit upon a telescope made of a weak objective lens and stronger, diverging, eyepiece lens. Galileo's telescope magnified more than had the work others had made (over the years Galileo made other, better telescopes). Galileo immediately made a telescope and gave it to the City of Venice. This allowed them to see whether grain boats or enemy ships were approaching on the Adriatic Sea. This was very advantageous for the city. Knowledge of enemy ships allowed them to raise a chain across the entrance to the Venice lagoon. This would break up the hull of the enemy ship. The City offered Galileo a job for life (which he took, but later got a more lucrative position at Florence).

Galileo built several telescopes. They might go for \$20 from Toys R Us today. They magnified about 20 times and had diameters about 1.5 inches.

Galileo turned his telescope to the heavens and quickly found that

- The Moon has mountains and craters, unlike the perfection predicted by Aristotle
- The Milky Way is made of lots of stars that had never before been seen
- Jupiter is accompanied by four moons. So NOT every body in the Universe circles the Earth (and which one has more moons?)

These discoveries were deeply disturbing to people. They differed from the status quo, and they seem to take the Earth from its most central place, by the existence of Jupiter's moons.

Galileo published his discoveries in Italian in a small pamphlet called "**Sidereal Messenger**" or "**Starry Messenger**" in 1610. This was rather like publishing scientific data in a supermarket tabloid rather than in a learned journal. Anyone could read it, and anyone could understand what Galileo had to say. He drew pictures of the positions of Jupiter's moons and of shadows cast by lunar craters to explain how he interpreted what had been seen.

In 1610-11 Galileo continued his observations. He found

- Saturn has three parts. Galileo never knew what they were
- The planet Venus has phases as predicted by Copernicus' model.
- The Sun has spots which come and go over days to weeks. The Sun rotates about once per 25 days at the equator. It is far from perfect and unchanging.

Galileo published these results in another book in Italian, **Letters on Sunspots**, in 1613

In 1611 Galileo took his telescope on a trip to show others what he had seen. He went to Rome, stopping to see astronomers on the way. Some people were convinced that Galileo was correct, others were unable to see through the telescope very well, others refused to even look. One astronomer, Clavius, suggested that the craters on the Moon were not the real surface. The real surface was a smooth crystal with the craters below.

Galileo was convinced of the correctness of Copernicus' model, but his observations show little direct evidence and no unequivocal proof. He did try to address the issue of discrepancies between the Copernican model and the Bible. He published a letter (1615) called "Letter to a Duchess" designed for the Duchess Christina who had asked one of Galileo's friends about the Copernican Theory. This letter suggests "The Bible tells us how to go to heaven, not how heaven goes." What did he mean by this?

Galileo went on to write that the Bible doesn't even mention all the planets. He thought that if there is an apparent disagreement between the Bible and an observation in the physical world, it must be because we do not understand what the Bible is saying. Do you think he was a religious person or not? How do you think that others took this?

Eventually the Church decided to do something. It was not clear whether the Ptolemaic or the Copernican theory was true, although many people in the Church were expecting that the Copernican theory would eventually be proved true. However there was still the issue of resolving the theory with the Bible and there still was no firm proof. In March 1616, a general proclamation was made saying that no one (that is no one Catholic who cared what the Church did) should teach the Copernican theory as the truth. It should only be taught as one among competing mathematical theories. If the evidence ever accumulated to the point that the Copernican theory was proven, then the interpretation of the Bible could be dealt with in the Church.

At this time, 1616, *De Revolutionibus* was banned. It was reissued in a "corrected" version with words inserted softening the assertions that the model with the Sun at the center was "true". A corrected version was published in 1620. The original was banned until 1835.

In February Galileo went to Rome and had a conversation with Cardinal Bellarmine. The Cardinal and Galileo knew one from another before Bellarmine was Cardinal. Galileo was asked whether he believed the Copernican theory. Galileo denied that he believed it. At this time, they may have discussed a special edict telling Galileo to refrain from discussing the Copernican theory at all. Galileo went home with a letter signed by Bellarmine refuting the idea that Galileo had been personally forbidden to examine the Copernican theory, but detailing the interaction.

Galileo went on with his work; Bellarmine and the Pope died. Pope Urban VIII ascended. He had discussed the Copernican theory with Galileo years before and had held the opinion that the Copernican might be correct. So Galileo thought that the climate might have changed.

Galileo put together his work on the "new", non-Aristotelian physics and the Copernican model in a book called "Dialog on Two Chief World Systems". The book is written as a series of four days of questions and answers. There are three characters, Sagredo, the moderator, Salviati, the supporter of the Copernican theory, and Simplicio, a supporter of Aristotle and Ptolemy. All of these names are names of friends of Galileo who were dead at the time the book was written.

Galileo tried to get the book approved, by giving the censor pages as they were written. The censor decided that the book was too complex and the review should await the complete book. When the book was complete, Galileo was in Florence and got permission for the censor in Florence to do the review. The book was approved, and given the stamp of approval, the *Imprimatur*.

When "Dialog on Two Chief World Systems" was published in 1632 and copies reached the Pope at Rome, the \_\_\_ hit the fan. We don't exactly know why, but Pope Urban VIII was angry. He

may have thought that the character Simplicio was a play on the Pope's name, he may have thought that Galileo had been told not to discuss the Copernican theory at all. We do know that Galileo was summoned to Rome to be tried by the Inquisition. Galileo delayed as much as he could and got to Rome in 1633. The Inquisition tried to recall all the copies of the book, but they had already been sold.

Unlike American courts, where the accused must be told the charge, the Inquisition would ask the accused what they thought the crime was. Galileo didn't know. The Inquisition brought out a document forbidding Galileo personally to discuss the Copernican theory at all. This was supposedly conveyed during Galileo's meeting with Cardinal Bellarmine in 1616. Such a document would normally be signed by the two parties and two witnesses who would be priests. The witnesses whose names were on this document were servants. Galileo brought out the letter from Cardinal Bellarmine describing the meeting, and NOT showing that Galileo had been given the edict.

The Inquisition was in a tough place. It would look really bad for them to say that they were wrong to accuse Galileo and the Pope wanted something done.

On the other hand, Galileo was in a tough place. He didn't want to be tortured, and he really didn't want to be burned at the stake. So he recanted, he swore formally that he did not believe that the Earth moves. He was allowed to go home to his estate Arcetri (near Florence) where he was put under house arrest for the rest of his life. His guards tried to prevent Galileo from communicating with other scientists. Galileo continues his research into the motion of bodies. He died in December 1642. Galileo's books on astronomy were on the prohibited list until 1835.

In 1979 the Church convened a group which, in 1992, concluded that it had been wrong to condemn Galileo.

#### Questions and Problems

- 1) If the Earth were flat, what would it look like as you sail away from a tree? Would it disappear from the top down?
- 2) How can we tell whether an alignment is a solar alignment or a lunar alignment?
- 3) Redraw the picture of solar motion, like the one at the beginning of the chapter, so that it represents the motion of the Sun as seen from Australia.
- 4) How did Aristotle's model explain the Moon rising and setting?
- 5) If Eratosthenes had measured that the angle between the Sun and the gnomon was  $10^\circ$  rather than about  $7^\circ$ , what would have happened to his value for the size of the Earth.

Answers 1) No, it should just get smaller and smaller. It might get lost in the mist before it gets too small to see. 2) The moon can go to declinations about  $5^\circ$  further north or further south of where the Sun ever rises or sets. This  $5^\circ$  of declination turns into 50 azimuth at the equator and more at every other latitude 3) Leave the background, earth, sky, NSEW points all the same. The rise and set points of the Sun could be the same, but tilt the paths toward the north. The June 21 path should go low and in the north, the Dec 21 path should go high 4) Ptolemy carries the Moon (and everything else) in its basic daily pattern 5) Put the  $10^\circ$  back into the ratio where  $7^\circ$  had been before. The distance will come out at 180,000 stades.