Lecture 9 and 10

Feb. 11 and Feb. 16. 2016

Astronomy: From Pythagoras to Ptolemy

# Recapping Aristotle’s geo-centric model:

1. A shimmering crystalline sphere which enclosed 9 concentric crystalline spheres.
2. The outermost sphere carried the millions and millions of fixed stars, while each inner concentric sphere carried the planet attached to it. All the spheres carried the heavenly bodies attached to them around the earth in a counter-clockwise direction, once a day, every day, without fail. The sun, please note, was included among the seven planets.
3. The earth did not move: it stood still in the center. The sun was considered a planet of the earth.
4. The heavenly bodies were qualitatively different from the earth: they were made of ether or quintessence (literally, the fifth essence) whose nature was to move in perfect circles. (Galileo will prove this wrong when he turned his telescope to heavens).
5. The sublumar sphere, from the moon to the earth was a sorry place – of decay and death etc. but heavens were perfect: they never deviated from their circular paths and had been doing that from the beginning of time…
6. Notice, the earth was the farthest from God, the prime mover. In Aristotle’s model, the further the planets/stars were from the earth, and closer they were to the Prime Mover, the more “noble” they were. More “noble’ planets more slowly than the less noble ones.

Even though everyone of the assumption behind the model turned out to be wrong, this model had a certain beauty and elegance. It provided a certain unity : the same four elements that made up the human body, made up the world that we inhabit, while the planets and the stars were made up of ether. It provided a pretty commonsense logic to why the earth should be in the center and why it should be a sphere. And it made room for God as Prime Mover, or the unmoved mover.

Even though they originated with Plato, followed by Aristotle, these assumptions entered Europe through Ptolemy’s *Almagest*. (more on Ptolemy will follow later in the lecture).

# Agenda

In this and the next lecture, we will be focusing on how Greek mathematicians and philosophers came up with many complex elaborations of the basic geo-centric model described above (and in more details in the previous lecture on Aristotle.) We will try to place Aristotle’s model in the larger paradigm of Greek astronomy that was set by the students of Pythagoras and Plato. This paradigm, we will see, was obsessed by a quest to explain the so-called “problem of the planets.”

Before we go any further, it is important to keep in mind how the sky looked to the ancient people, who had nothing but their eyes to observe the stars.

# KNOWN EMPIRICAL FACTS ABOUT THE STARS AND THE PLANETS:

The Ancients had only their eyes to observe the sky with. On a clear night, they could see thousands of points of light scattered all over the sky. It must have been a beautiful sight, for it seems to have inspired many poets and artists. Shakespeare, for e.g., called the stars “night’s candles,” while Milton described the Milky Way as “a broad and ample road, whose dust is gold and pavement stars.”

It is a remarkable achievement that they could distinguish FIVE points of light – which they called planets ( planets is the English translation for “wanderers” in Greek) – from the thousands of others. The distinction was based upon difference in the movement of those points of light they called “stars” and the five points of light they called the “planets.” The ancients Greeks knew only five planets: Mercury, Venus, Mars, Jupiter, Staurn. ( Ancient Indians admitted nine grahas, or NAVGRAHA? That is because they included the sun, the moon, Rahu and Ketu).

Naked eye observation revealed the following facts about the stars and the planets, which the ancient models tried to explain:

Movement of the Sun:

As far back as the Babylonians and the Egyptians, ancient people have been making systematic observation of the motion of the sun.

For this purpose, they developed a primitive sun-dial consisting of a measured stick, the GNOMON (pronounced No-Mon), projecting vertically from a smooth flat surface. Since the apparent position of the sun, the tip of the gnomon and the tip of its shadow lie on a straight line, measurements of the length of the shadow completely determine the direction of the sun. When the shadow is short, the sun is high in the sky, when the shadow points to the East, the sun must be in the West. In antiquity, the sun’s motion, as measured by the gnomon’s shadow was used to keep time and track the seasons.

Using this technique, ancients had figured out a few useful facts: (see diagrams attached as pdfs in this folder)

* The shadow of the gnomon is shortest at noon, when the sun is directly above, and the longest at sunrise and sunset. During the daylight hours, the shadow moves gradually through a systematic fan-shaped figure as shown in the diagram (below).
* At the instant of each day when the shadow is the shortest, it always points in the same direction. In the northern hemisphere, this direction is taken as the North and the time when it is the shortest is taken to be the noon.
* Winter solstice (first day of winter, the shortest day of the year, which falls around Dec. 21), the sun is at its most southerly position on the eastern horizon. That is, the sun rises and sets farthest to the south of horizon.
* Summer solstice: the sun rises on its most northern position,, around June 21. It is the longest day and the shortest night.
* Spring equinox, on or around March 22, the sun rises almost exactly due East. Day and night are close to being equal in length on equinox.
* Autumn equinox, September 23, when the day and the night are equal again.

Sun’s drift with respect to the fixed stars: The sun’s position with respect to the fixed stars changes from day to day. Each day, the Sun is in a slightly more eastward position with respect to the fixed stars: that is what lies at the basis of zodiacal horoscopes.

The movement of the moon:

The moon, like the sun, rises in the east and sets in the west. It goes through phases, taking a little over 29 d. to complete a cycle. Whatever phase it in today, it will be in that phase 29 days later.

Like the sun, the moon also drifts eastward with respect to the fixed stars. The moon returns to the same spot with respect to the fixed stars about every 27 days. This is the basis of lunar astrology, based upon nakshatar.

The movement of stars:

Stars move in a regular pattern, which repeats every 24 hrs. For example, suppose you live in Northern hemisphere, and you go out at 9 pm for some stargazing. Suppose you focus on the cluster of seven stars we call saptarishi in India or the Big Dipper in the West.

During the night, you will see the Big Dipper moving in a circular motion, counter-clockwise, around the North star, or what we call dhruv tara in Hindi. If you stood out there for 24 hours, you will lose sight of the Big Dipper during the day, but when darkness returns, you will see the big dipper again continuing on the same course around the North star. The next night, you will find the entire show being repeated, pretty much in the same position that it was the previous night.

In short, the Big Dipper and other stars near the North Star appear to follow a circular path, with the North Star at the center. They complete the circle once every 24 hours.

Stars that are lower down the sky, or closer to the horizon, also show circular motion: you will find them rising from the eastern horizon, moving in an arch and setting in the West, pretty much like the Sun. The same star clusters keep rising and setting each evening, pretty much in the same segment of the sky every night.

Finally, as a particular star or a star cluster moves across the sky, it remains in the same position with respect to other stars or star clusters: That it, stars move as a group across the night sky and maintain a

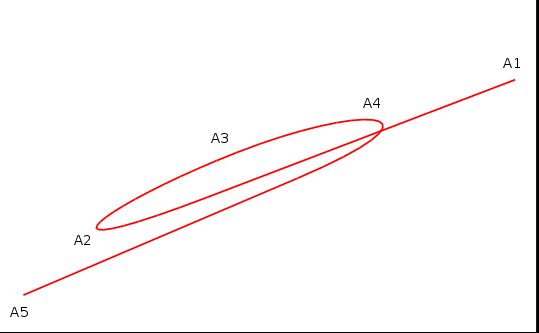
fixed relationship with other stars. This is why they are called “fixed stars.” These clusters of fixed stars are called constellations.

Movement of the planets:

To the naked eye on any night, a planet looks like any other point of light. Points of light don’t come with labels “stars” or “planets.” WE have learned to distinguish between them, primarily by their curious movement.

Keep watching say, Jupiter. Every night, it will be slightly eastward to the fixed stars than it was the previous night and over the course of weeks and months, it would be significantly east of any particular star constellation.

Planets show retrograde movement, that is, they appear to move backward from their usual course. E.g., mars usually drifts eastward each night, with respect to fixed stars, but about every two years, Mars will drift westward for a few weeks before it resumes its motion eastward. This is called retrograde motion.



Apparent path of Mars in 2009-2010 relative to the [constellation Cancer](http://en.wikipedia.org/wiki/Cancer_%28constellation%29).

(see the PowerPoint included with this lecture for actual photographs of planetary regression. I highly recommend the website called “The World at Night” at <http://www.twanight.org/newtwan/index.asp>. Look for pictures by a Turkish astro-photographer by the name of [Tunc Tezel](http://www.twanight.org/newtwan/photographers_about.asp?photographer=Tunc%20Tezel))

Explaining the strange behavior of these “wandering stars’’ would become THE CENTRAL QUESTION for astronomy in the West for nearly 2000 years.

To fully understand how the Greeks tried to understand the strange behavior of planets, we will quickly review the history of astronomy from Pythagoras to Plato and then look at the famous “homework” Plato assigned to his students.

Let us quickly review how planetary problem was “solved” by Greek astronomers, leading up to Ptolemy’s very influential model. We will go back to Pythagoras and his students for a while to fully understand the Greek astronomy.

History of astronomy from Pythagoras to Plato:

In this roughly three centuries between Pythagoras, Plato and Aristotle, we come across some very rudimentary ideas about helio (sun). These ancient ideas will be later revived by Copernicus, Tycho Brahe and Kepler. But in their own time, these ideas were mere speculations that were overshadowed by Plato’s insistence upon a stationary earth and circular motion of stars and planets. Some of the important early astronomical speculations include the following:

**“Central fire” or “the hearth of Zeus”**: Pythagoras ‘s student, by the name of Philolaus (470–c. 385 BCE) proposed that the daily revolution of the heavens is an illusion. Perhaps it is the **earth** that is revolving, and *we standing on the earth*, *only imagine that the heavens are going around us*. He proposed that everything would be simpler if we assumed that it was the earth that was moving.

So he proposed that the earth moved around an external point in space which he called the “central fire” or the “ the hearth of Zeus.” This fire IS NOT THE SUN. Unlike the sun, this fire could not be seen because, Philolaus said, Greece was permanently turned away from it, just as the dark side of the moon is permanently turned away from the earth. Between the earth and the central fire, he placed an invisible planet, which he called the *antichton*, or the counter-earth, whose function was to protect the earth from being burnt by the central fire.

Around the central fire, then, revolved the concentric orbits – antichton being the innermost, followed by the earth, the moon, the sun, the five planets and the fixed stars…

Copernicus mentioned Philolaus as one of his inspirations for proposing a sun-centered model …

**Half-way between Geo and Helio=centric model**: HERAKLEIDES (390 BC – c. 310 BC) student of Plato and Aristotle, both.

He accepted the idea that the earth moves, but dropped the central fire and replaced it with rotation around earth’s axis. The reason was that Greek seafarers (sailors) who had gone as far east as India had failed to see the central fire. So HeraK keeps the idea that the earth moves, but drops the central fire.

HeraK noticed that the Venus and Mercury always stayed close to the sun, as they did their zig-zag in the sky. He proposed that Venus and Mercury are planets of the Sun – i.e., revolve around the sun, as the sun revolves around the earth. (Curiously enough, a model very close to this one will be later proposed by Tyco de Brahe, a colleague of Kepler.

**Sun-centered universe:** Aristarchus (b. 310), last of Pythagoreans, claimed that the sun, not the earth was at the center. His works where he puts the sun in the center is lost, but later Greek and Roman scientists/philosophers refer to his sun-centered cosmos. The following quote from Archimedes should explain what Aristarchus was up to (pay extra attention to the italicized part)

Though the original text has been lost, a reference in [Archimedes](http://en.wikipedia.org/wiki/Archimedes)' book [*The Sand Reckoner*](http://en.wikipedia.org/wiki/The_Sand_Reckoner) (*Archimedis Syracusani Arenarius & Dimensio Circuli*) describes another work by Aristarchus in which he advanced the heliocentric model as an alternative [hypothesis](http://en.wikipedia.org/wiki/Hypothesis). Archimedes wrote:

You (King Gelon) are aware the 'universe' is the name given by most astronomers to the sphere the center of which is the center of the Earth, while its radius is equal to the straight line between the center of the Sun and the center of the Earth. This is the common account as you have heard from astronomers. *But Aristarchus has brought out a book consisting of certain hypotheses, wherein it appears, as a consequence of the assumptions made, that the universe is many times greater than the 'universe' just mentioned. His hypotheses are that the fixed stars and the Sun remain unmoved, that the Earth revolves about the Sun on the circumference of a circle, the Sun lying in the middle of the Floor, and that the sphere of the fixed* [*stars*](http://en.wikipedia.org/wiki/Star)*, situated about the same center as the Sun, is so great that the circle in which he supposes the Earth to revolve bears such a proportion to the distance of the fixed stars as the center of the sphere bears to its surface*.[[2]](http://en.wikipedia.org/wiki/Aristarchus_of_Samos#cite_note-1)

—[The Sand Reckoner](http://en.wikipedia.org/wiki/The_Sand_Reckoner) (from Wikipedia).

It is no wonder that Aristarchus has been called the “Greek Copernicus.”

Plato’s famous “homework”:

By the time Plato appears on the scene, the Greeks had figured out that planets don’t fit into the circular dogma: their movement in not circular, but rather they appear to zig-zag.

**But rather than give up the circle, Greek astronomers tried to fit the planetary motion within the circular dogma**.

It was Plato who set the paradigm of Greek astronomy: Plato, as we have already see, believed that the world was constructed with geometric simplicity and elegance, and that all the heavenly bodies have a natural circular motion, since that is the simplest uniform motion that repeats itself endlessly. Because of his Pythagorean beliefs in the divinity of heavenly bodies, the perfection of circles and his geometric cosmology (recall those regular solids), Plato firmly believed that the zig-zag motion of planets was only an optical illusion and that the planets ACTUALLY moved in perfect circles. Plato, if you remember, treated sensory knowledge as inferior; true knowledge for him was to be acquired through thinking, logic and contemplation. So he thought that “wandering” behavior of planets was simply due to our defective and limited senses. TRUE philosophers can go behind the appearance and realize that the REAL motion was actually in circles.

Plato, therefore, challenged his students at the Academy to find a way to describe the irregular, zig-zag motion of planets in terms of perfect circles. Plato suggested that perhaps these complicated paths were actually *combinations* of simple circular motions, and challenged his Athenian colleagues to prove it. In fact, Plato challenged his students at the Academy to come up with ideas that could describe the zig-zag motion in terms of circles.

He wanted his students to go behind the appearance to find the ideal mathematical forms which, he insisted, was a perfect circle. He was basically challenging his students to apply critical mathematical reasoning to empirical observations to find the REAL pattern of heavenly motion.

Plato’s challenge set the agenda of astronomy for many centuries, right up to Kepler in the 16th century who would finally give up on circles. The task of astronomy was now to prove that the apparently irregular meanderings of the planets were the result of some combination of several simple, circular uniform motions. The goal of ancient astronomers was to reduce the intricate, variable motion of each planet and reduce it to some combination of uniform circular motion.

Let us look at some of the solutions to Plato’s challenge

1. Eudoxus of Cnidus (390-337 bce) was the first to tackle the problem. He was a mathematician at Plato’s Academy. He proposed an ingenious solution to the problem of planetary motion.

He assigned to each planet not one but several concentric spheres. Every planet is supposed to participate in all the independent rotation of all the various spheres which form its nest. By allowing each sphere to rotate at different tilt and speed, it was possible to reproduce roughly the actual motion of each planet.

Eudoxus assigned:

Three spheres each to the moon and the sun

Four spheres each to the five planets.

Thus he proposed a total of 26 spheres, including the sphere of the fixed stars.

There spheres were not real physical spheres. Eudox introduced them purely as tools for mathematical calculations.

How did adding all these sphere solve Plato’s problem? The following example may help you to understand Eudox’s solution:

Let us suppose the outermost sphere for the planet Mars rotates uniformly once a day and that accounts for the planets daily rising and setting;

The second sphere also rotates around its axis (which is titled with respect to the outermost circle). But Eudox made this second sphere rotate in the opposite direction, once in 687 days. This motion accounted for Mars’s slow west-to-east motion.

The two innermost spheres account for the retrograde motion.

Mars itself is attached to the equator of the innermost sphere and participates in the motion of ALL the other three spheres. The resulting motion of the planet is a composite of motion of all the four spheres.

Notice: Eudox has nothing but circles in his model – thus solving Plato’s problem.

1. Callippus of Cyzicus (370 bce) added more spheres raising the total number to 34
2. Aristotle: followed the pattern set by Eudoxus and Callippus . He added more spheres bringing the number to 55.

Why? What were the additional spheres doing?

He HAD to add more spheres because in his understanding of nature, void, or empty space is impossible. If there is no empty space between Eudoxian spheres, the motion of each will be transmitted to the next one. So he postulates the existence of “counteracting” spheres which spin in the opposite direction from their neighbor, and therefore (supposedly) cancel the motion.

Eudoxus and Calippus were not concerned with a model that would be physically possible; they were not concerned with the real machinery of the skies. They were constructing a purely geometrical model.

But Aristotle wanted to do better. He wanted to transform the model into a truly physical model. The difficulty was that the all adjoining spheres must be connected, but the individual motions should not be transmitted to the other spheres. So A. inserted a number of extra ‘neutralizing sphere’ which turned in opposite direction and insulted each “nest” from the motion of the next,

# From Aristotle to Ptolemy, or from Athens to Alexandria.

After Aristotle, the center of astronomy moves from the Lyceum in Athens to the Museum and the library in Alexandria, the great Egyptian city named after Alexander the Great. Alexander dramatically enlarged the Greek territory, carrying Greek culture and language as far east as Hindu Kush in Afghanistan, across the Indus river in into N. India, and as south as Egypt. The synthesis of Greek with local cultures is called “Hellenistic” or Greekish.

Two important astronomers stand out from Alexandria:

Hipparchus (fl 140 BCE) was an extremely productive and innovative mathematic and observational astronomer who work is stuff of history books. When it came to observations: he is credited with a map of the sky in which he mapped 1000 stars. He came up with a classification for brightness of the stars, a scale that is still used in astronomy. He set up an observatory in Rhodes Island in the Aegean sea.

His importance lies in his mathematical modeling of planetary motion which Ptolemy used in his model. He accepted Aristotle’s circular dogma but reduced the number of spheres in Aristotle’s model from 55 to seven. He came up with the idea of epicycles: each planet was supposed to orbit a focal point on a sphere that was going around the earth. (more on epicycles below).

2. Claudius Ptolemy (85 -165 CE. NOTICE, WE ARE NOW INTO THE COMMON ERA). Aristotle’s earth-centered, circular-motion universe was further refined by the Egyptian astronomer by the name of Claudius Ptolemy who lived in Alexandria form around 85 to 165 CE. Ptolemy’s monumental work was called *Megale mathematike syntaxis* (“Great Mathematical Composition”) or simply *Megiste* (“the greatest”). It mapped and charted the visible stars. The star charts were useful for ocean navigation. Ptolemy’s work was forgotten under the Roman Empire. Later Arab scholar rediscovered the work, translated it from Greek into Arabic. They added the Arabic word al before Megistge and called it Almagest, meaning the greatest. The *Almagest* became the source book of astronomy in Renaissance Europe and it is this model that Copernicus engaged with –and refuted. EVEN THOUGH IT WAS EVENTUALLY OVERTHROWN, PTOLEMY’S ALAMAGEST remained the Bible of astronomy until the beginning of the 17th century.

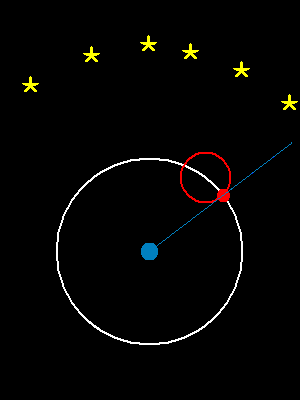
Ptolemy accepted all the three dogmas of Aristotle (see the beginning of the last lecture). He was totally committed to the circular dogma. Here are two quotations from Almagest:

“we believe the object which the astronomer must strive for is this: to demonstrate that all phenomena in the sky are produced by uniform circular motions.”

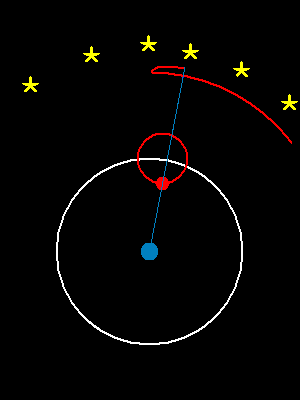
“[our task is ] to prove that the apparent irregularities of the five planets, the sun and the moon can all be represented by uniform circular motions, because only such motions are appropriate to their divine natures… [this] is the ultimate aim of mathematical science.”

Ptolemy retained the requirement of uniform circular motion, but instead of applying this requirement to spheres, he adopted Hipparchus’s epicycles. His model is called “epicycles on deferent” model. It has been described as the “ferris wheel model” as opposed to Aristotle’s “onion model”. This model introduced two terms which you must know, because they will be challenged later during the Copernican Revolution: “Epicycle” and “Equant”.

EPICYCLE: (Please see the website <http://faculty.fullerton.edu/cmcconnell/Planets.html> for working models of epicylces and equat point. This will help you understand the concepts).   
Claudius Ptolemy approached the problem of modelling the motions of the planets with a greater emphasis on accurate prediction. He utilized an entirely different geometric model to account for the retrograde motion of planets, a device known as an *epicycle on deferent*. In the figure below, the white circle is the *deferent*, which carries the red circle (the *epicycle*) around the earth. The planet Mars (the small closed red circle) thus tumbles around the sky according to the combination of two uniform circular motions. The resultant path of the planet as seen from the ground periodically moves backwards compared to the overall motion of the planet.



* Let the bigger circle (white in the color picture above) represent a circular orbit around the earth. This is called a *deferent* in this system . The center of this orbit may or not be the Earth. If the center does not correspond to the earth, it is called *eccentric*
* Draw a small circle, or an epicycle, with its center on the circumference of the deferent .
* The planet sits on the epicycle and moves uniformly, counterclockwise, around the epicycle.
* Meanwhile, the center of the epicycle moves uniformly, counterclockwise, around the deference circle.
* The observer on the earth sees the composite of two uniformly circular motions – i.e. the motion of the planet around the epicycle and the motion of the deferent around the epicycle.
* When the motion of P about the epicycle is greater than the motion of the epicycle along the deferent, the planet will appear to reverse itself and undergo a period of retrograde motion.
* Ptolemy’s model was flexible: by varying the diameter of the epicycle and the speeds of planets, you could predict. It was efficient at prediction of eclipses etc.



Another way to understand Ptolemy’s model is to imagine a giant Ferris wheel: a huge, upright slowly revolving wheel with seats or small cabins handing suspended from its rim. Let us imagine the passenger is safely strapped in the seat. Let us imagine that the machinery has gone a bit crazy: Instead of hanging down quietly from the rim of the big wheel, the cabin begins to revolve around the pivot from which it is suspended, while the pivot itself slowly revolves with the big wheel

This revolving cabin is the equivalent of planets rotating in epicycles the centers of which are rotating around the earth.

Now, this cabin/planet is now describing a curve in the space which is NOT a circle, but is nevertheless produced by a combination of circular motions. By varying the size of the big wheel (i.e., the orbit), the length of the arm by which the cab in is suspended (il.e., the radius of the epicycle) and the speed of the two rotations, an amazing variety of curves can be produced.

Seen from the earth, which is the center of the Big Wheel, the passenger/planet in the cabin will look like he/it is moving clockwise until the stationary point S1, then regress anti-clockwise to S2, then move clockwise to S3 and so on. The rim of the Big Wheel is called the DEFERENT, the circle described by the cabin is the EPICYCLE.

By the time Ptolemy’s system was perfected, the seven passengers – the sun, moon and five planets – needed a machinery of no less than 39 wheels to move through the sky. The outmost wheel which carried the fixed stars made the number an even 40.

EQUANT:

This was introduced to take care of the OTHER dogma, namely, uniform motion of heavenly bodies.

Planets move in uniform motion – neither slowing down, nor accelerating, sweeping the same angle with respect to the center in a unit of time – around the epicycle.

But what about the motion of the center of the epicycle? Is the epicycle itself moving at a uniform speed around the orbit?

When the center of the epicycle is measured from the center of the earth, the motion of the planet is not uniform.

So Ptolemy chose to make the motion of P’s epicycle uniform relative to some other point rather than the center of the earth. This point is called EQUANT.

EQUANT point is the place/point from which the measurement had to made for the epicycle to move at a uniform speed with respect to the observer on the earth.

WHAT IS THE STATUS OF EPICYLES and EQUANT points?

These were considered mathematical devices for saving the appearances, i.e., explaining the retrograde movement of the stars , while adhering to the Aristotelian model of earth-centered universe where heavenly bodies move in perfect spheres at a uniform speed.

Any earth-centered approach needs epicycles in order to account for the retrograde motion of the planets. (Remember: retrograde motion is when the planets appear to move “backward” from their usual motion.)