Classical Antiquity

Classical antiquity is a time period that extends roughly form 600 B.C. to 500 A.D., and for our purposes mainly concerns the civilizations of Greece and Rome. Geographically, it refers to the lands bordering the Mediterranean Sea, the modern nations of Greece and Italy, as well as much of what we now call the Middle East – Egypt, Israel, Syria, Iraq (Mesopotamia), Iran (Persia) and Turkey (Asia Minor). Throughout this essay the personalities here will be referred to as "Greeks", although they lived throughout the eastern Mediterranean under a variety of political regimes. They are Greeks in that they were all part of Greek (***Hellenistic***) culture - a culture that in one form or another spanned nearly one thousand years, and continued throughout the Roman period.

The Greeks were unique among ancient cultures in the questions they asked. Referring to a famous quote by Bertrand Russell, when they asked "why", they meant, "*What previous circumstances led to the current event*?" not "*What is the purpose of this event*?" In other words, the Greek question is ***"How does it work?"*** not ***"What does it mean?"*** When inquiring about astronomy, their answers nearly always involved mathematics, particularly geometry. Generally speaking they were not scientists in the sense that we use the term today, because it appears that they expended little effort in experimentation or in systematically collecting data. Even so, their achievements in understanding the universe are remarkable. By the end of the classical period many features of the universe that we accept today had been established, and it would be 1,500 years before significant advances beyond the Greek achievement were made.

Thales (624 B.C. – 547 B.C.)

Thales was born in the busy Ionian seaport town of Miletus (Ionia forms the western coast of modern Turkey), and is usually considered the "***Father of Philosophy***". This pride of place derives from the fact that he is the first person of record that attempts to explain the nature of reality on purely rational grounds. He is usually best known for his view that the underling substance of the universe is water. He probably arrived at this opinion by observing that water can be manifest as all three known forms of matter: a liquid (the most common), a solid (ice) and a gas (steam). He also had a purely mechanical model of the universe. In his view, the earth is a disk floating on a body of water, enveloped by a dome to which is attached sun, moon, and planets. For Thales, natural phenomena do not arise from the capricious whims of supernatural forces, but are the direct and logical consequences of how the universe is structured. For example, earthquakes can be explained by high waves buffeting the floating earth. This explanation should be contrasted with the then prevailing mythological view that earthquakes were caused by angry stirrings of Poseidon, god of the sea. Thales' model of the earth was discredited even in ancient times; he is given a place of honor in intellectual history for his ***questions*** *(How do things work?)*, not for his answers.

Pythagoras (570 B.C. – 490 B.C.)

Pythagoras was born on the island of Samos off the coast of Ionia, just a few miles from Thales hometown of Miletus on the mainland. Students the world over know him from the *Pythagorean theorem* (the square of the hypotenuse of a right triangle is equal to the sum of the squares of the other two sides). Pythagoras founded a school of mystics who believed that mathematics was the key to understanding the universe. They attached special importance to regular geometric forms, especially the sphere. They believed heaven to be a perfect sphere surrounding the earth, a belief no doubt derived from simple observation of the sky. Further, they believed that celestial bodies – the sun, the moon and the planets were themselves spheres. In fact, they were the first known advocates of a spherical earth, although, as far as known, they did not present arguments to support this theory. In modified form, the Pythagorian's view of the primacy of mathematics in understanding nature can be found to this day in much of science, especially in theoretical physics.

Anaxagoras (499 B.C. – 428 B.C.)

Anaxagoras was another Ionian, born near what is now the city of Izmar in Turkey. He is noted for proposing that the sun is a red hot stone and that the moon has no light of its own, but only the reflected light of the sun. Further, he asserted that solar eclipses arise when the moon is between the sun and the earth and that lunar eclipses occur when the earth is exactly between the sun and the moon. He is the first person of record known to have held these views, and because of this he was imprisoned by the civic authorities and accused of blasphemy. It was blasphemy because the sun at that time was considered divine. Anaxagoras' problems provide a vivid reminder that not all Greeks were in the business of explaining nature in terms of natural law!

Democritus (460 B.C. – 348 B.C.)

Democritus, born in the mainland Greek city of Abedra, is perhaps the most modern sounding of the early Greeks. He is best known as the founder of the ***atomistic*** school of thought, the idea that there is an ultimately smallest particle of matter called an ***atom*** that is both ***invisible*** and ***indivisible***. Although what we call atoms today have neither of these properties (large atoms can be imaged with scanning electron microscopes and they can be further subdivided into subatomic particles such as electrons, protons and neutrons), our modern theory of matter traces its ancient roots to the philosophy of Democritus. Another modern sounding belief of the atomists was that the world originated from the coalescing of atoms scattered randomly through empty space. The most famous quotation attributed to Democritus is: "*Nothing exists but atoms and empty space. Everything else is opinion.*" With some modification of terminology, a modern cosmologist could say something very similar today.

Plato (428 B.C. – 348 B.C.)

Plato founded a school (the Academy) in Athens and his teachings are considered the ultimate foundation for much of subsequent western philosophy. He was definitely not an astronomer, being more interested in epistemology, ethics and other aspects of philosophy, but he did pose problems for future generations of astronomers to struggle with. By Plato's time, virtually all Greek philosophers had accepted the notion that the sphere and the circle represented geometrical perfection, and, therefore, all celestial bodies - sun, moon and planets – along with the earth, were spherical in shape. Further, all celestial motion must be uniform and follow perfectly circular paths. The problem with this point of view is that, while the sky certainly appears to be spherical, the motions of the sun, moon and the planets are definitely not uniform (each of these objects move at different rates at different times). In addition, the planets seem to stop from time to time and reverse their direction of motion (retrograde), tracing out loops through the constellations; not at all what would be expected from motion around the circumference of a circle. Plato was not particularly worried about this, since his belief was that the senses were unreliable guides in the search for truth. He posed the following problem for his students: find a combination of uniform circular motions that to the senses will appear to mimic the motions of the sun, moon and planets. A number of ingenious schemes were proposed both in Plato's time and later.

Eudoxus of Cnidus (400 B.C.E – 347 B.C.)

Eudoxus was one student of Plato's who got an A in the class - he came up with a scheme that would do pretty much what the teacher wanted. Eudoxus' universe consisted of a spherical earth surrounded by a series of nested spheres, all turning on different axes, and each carrying one of the celestial bodies (sun, moon and planets). The system was quite complicated, especially for the planets (each planet required more than one sphere), but it could be made to work if the various spheres could be spun at arbitrary rates and in arbitrary directions. Eudoxus made no claim that his spheres were real in the physical sense. They were simply mathematical devices for calculating the positions of the planets.

Aristotle (384 B.C. - 322 B.C.)

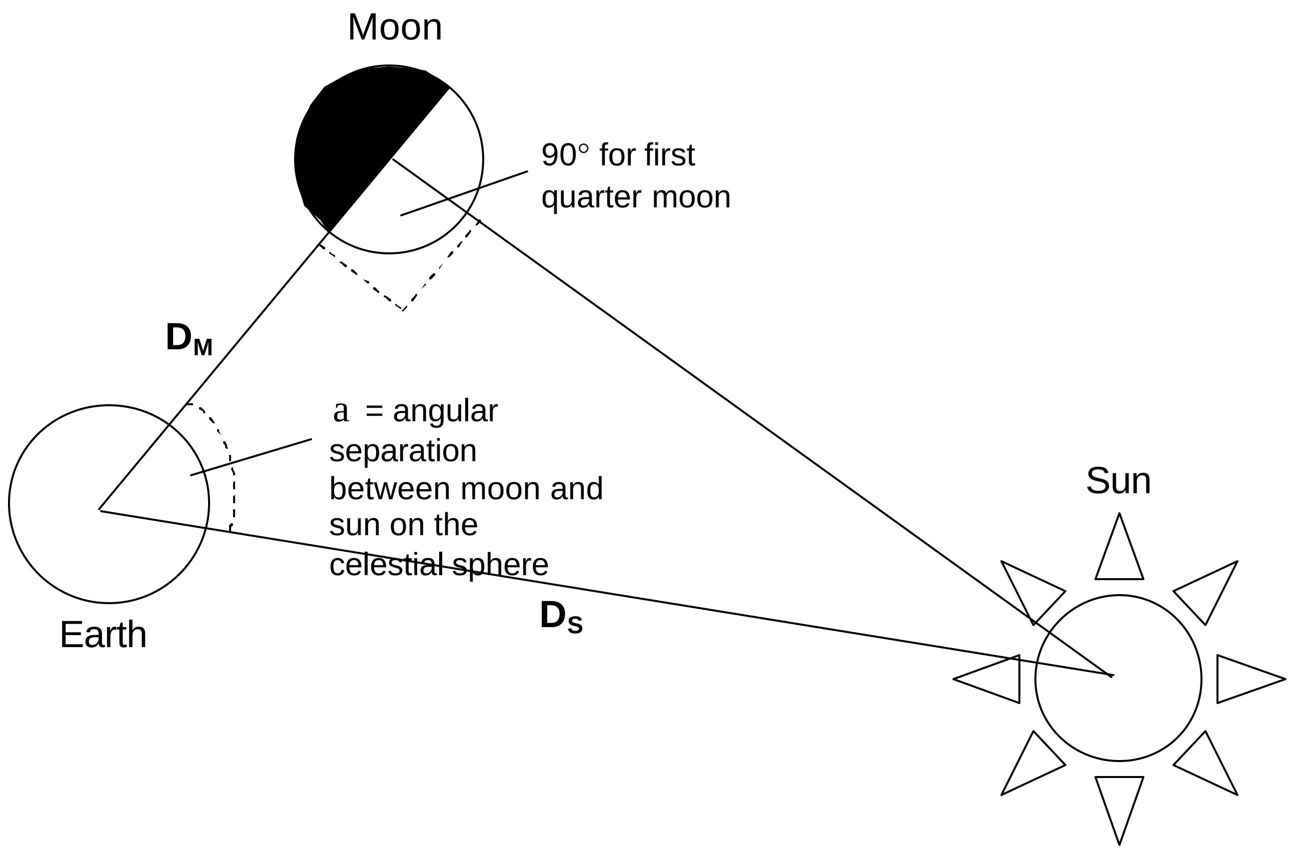
Aristotle, originally from Macedonia, was Plato's star pupil. Aristotle was much more interested in the natural world than his teacher and wrote books on biology, physics and astronomy that had a profound influence on scholarship for the next 1500 years. His thinking on astronomy is summarized in the book entitled ***On the Heavens***. Here, he accepts that the earth is a sphere and he also embraces Eudoxus' geocentric model of the universe (concentric celestial spheres). Unlike the Pythagoreans, Aristotle gave rational reasons why the earth is spherical. He pointed out that the shadow of the earth on the moon during a lunar eclipse is always circular, very unlike the changing shadow shapes during monthly phases. Since a sphere is the only geometric form that always casts a circular shadow, it follows that the earth is a sphere. Another piece of evidence he cites in favor of a spherical earth is that the locations of familiar stars with respect to the horizon change dramatically as you travel north or south. As you go north, northern stars rise higher in the sky, while stars near the southern horizon disappear. Conversely, when you travel south, stars previously hidden below the southern horizon rise above it and become visible, while northern stars descend in altitude. He also believed that Eudoxus' spheres were real physical entities. To address the problem of the strange mechanical properties such spheres would have the have (no friction, for example), he postulated that the substance of the heavens was perfect and different in kind and quality from the corruptible substance of the earth. In the centuries that followed this was taken to mean that the heavens were unchanging. Thus, phenomena like comets that appear for a few weeks then vanish were believed to be artifacts of the atmosphere, not something occurring in the perfect heavenly realm beyond the confines of the earth.

Aristarchus (310 B.C. – 230 B.C.)

Aristarchus, like Pythagoras from the island of Samos, is more what we think of as an astronomer today. He is best known for two things: (1) he measured the distance and size of both the sun and the moon, and (2) he proposed a heliocentric (sun-centered) model of the solar system.

His distance measurements involved a through understanding of geometry and were quite ingenious. For example, when the moon is in its first quarter phase, the relationship between the earth, the sun and the moon is as shown the diagram below. A line drawn from the center of the sun to the center of the moon will form a right angle with the ***terminator***, the line dividing the moon's bright and dark halves. A line drawn from the center of the earth to the center of the moon will lie exactly along the terminator and this line will form an angle ***a*** with a line drawn from the center of the earth to the center of the sun. In principle, the angle ***a*** can be measured, since it is simply the angular separation between the sun and the moon on the celestial when the moon is exactly first quarter. As you can see from the diagram, the earth-moon, moon-sun and earth-sun lines form a triangle. Since the three angles of a triangle always sum to 180 degrees, all of the angles are known. So if the length of one side is known, then we can find the length of all other sides. Unfortunately, Aristarchus didn't know even one side of the triangle, so his results were relative. According to his results the sun is about 20 times further from the earth than the moon. Although Aristarchus correctly concluded that the sun's distance from the earth is considerably greater than the moon's, the number is wrong (the sun is really about 400 times more distant). His method was perfectly sound; the problem lay with the measurement of angle

a. Aristarchus found this to be 87 degrees, while it is actually 89.8 degrees. This is so close to 90 that he could not possibly have accurately measured this angle with the instruments available to him.



To estimate sizes, Aristarchus began by noting that the sun and the moon appear to be the same size on the celestial sphere; this is demonstrated during every solar eclipse when the moon just covers the sun. But if the sun is 20 times further away, it follows that the sun must be 20 times larger than the moon; otherwise the sun and the moon would not appear to be the same size. How do these sizes relate to the size of the earth? For this Aristarchus used the size of the shadow earth casts on the moon during a lunar eclipse. From his measurements (or estimates he obtained from others- it's not clear) he concluded that the earth's shadow on the moon is about twice the moon's apparent diameter. Working from geometrical shadow diagrams and the (presumably) known distance to the sun, he concluded that the earth's diameter is about three times that of the moon. Again, a perfectly sound method with a wrong result (the earth's diameter is actually four times that of the moon), but the qualitative conclusion still holds: the earth is larger than the moon. Finally, since the sun is 20 times larger than the moon, it follows that the sun is also larger than the earth. According to Aristarchus' numbers, 20/3 = 6.7 times larger.

Thus, despite practical problems with measurement, the rough dimensions of the earth – sun - moon system were coming into focus some two centuries before the birth of Christ. Unfortunately, Aristarchus' writings on his most startling theory – that the earth moves around the sun – have been lost, so we don't know what arguments he used to defend this unpopular belief. What we know about his ***heliocentric*** (sun centered) cosmology comes exclusively from other ancient writers, most opposed to the idea. Archimedes (287-212 B.C.) gives a short summary of Aristarchus' thinking:

"Aristarchus of Samos brought out a book consisting of certain hypotheses, in which the premises lead to the conclusion that the universe is many times greater than it is presently thought to be. His hypotheses are that the fixed stars and the sun remain motionless, that the earth revolves about the sun in the circumference of a circle, the sun lying in the middle of the orbit, and that the sphere of the fixed stars, situated about the same center as the sun, is so great that the circular orbit of the earth is as small as a point compared with that sphere."

- Archimedes (excerpt in The Book of the Cosmos edited by Dennis R. Danielson)

Many scholars are convinced that Aristarchus must have arrived at his position based on the knowledge that the sun was much larger than either the earth or the moon. This coupled with the fact that the sun is clearly vital to all life on earth (a fact that the Egyptians, among others, elevated to a religion) must have made a compelling argument that it and not the earth was central to the organization of the cosmos. However, arguments against the idea are also compelling: If the earth is moving why don't we notice it? If the earth is sometimes on one side of the sun and sometimes on the other, then during the course of a year we are viewing the celestial sphere from different vantage points and this should make some of the stars appear to shift position (parallax). Why has this never been observed?

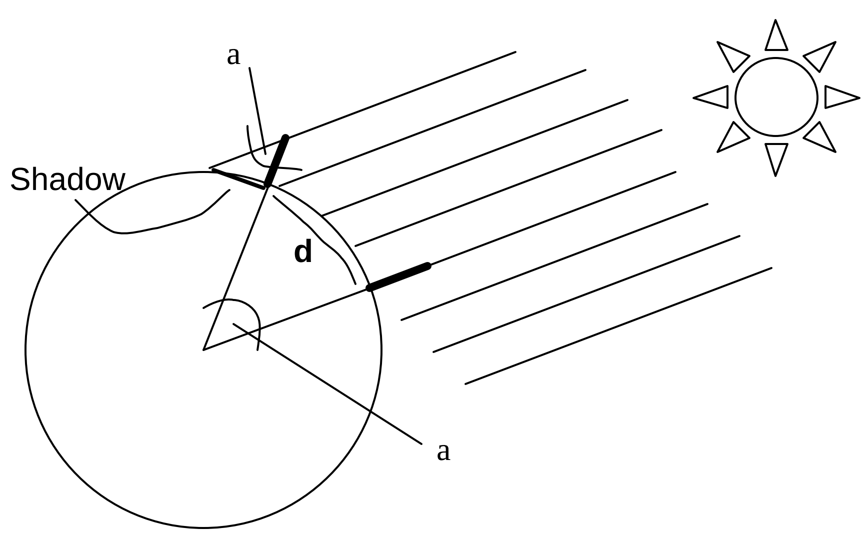
Eratosthenes (276 B.C. – 195 B.C.)

Eratosthenes was the Chief Librarian of the great library at Alexandria on the coast of Egypt. During the classical period this library was the greatest depository of knowledge in the world. Although he had many interests, Erotosthenes is best known to astronomers for measuring the circumference of the earth. He accomplished this by noting the different lengths of the shadows cast by upright poles in Alexandria and in Syene, a city to the south down the Nile. As it happens, Syene is situated on the Tropic of Cancer. Therefore, at noon on June 21st (the summer solstice) an upright pole at Syene will cast no shadow, since the sun will be directly overhead. However, further north in Alexandria on that same date, a measurable shadow will be observed, since the sun is always south of the zenith.

The method is illustrated in the diagram below. First, the length of the shadow from the pole in Alexandria is measured. Knowing the length of the pole, the length of the shadow and the fact that the pole makes a right angle with the ground allows the angle a to be determined**.** From the rules of geometry (the interior angles of a line intersecting two parallel lines are equal) this angle is the same as the angular separation between the two cities. Eratosthenes found a to be about 6 degrees**.** After finding the angle, the distance ***d*** between the two cities had to be determined in units of length, *stades* in Erasthenes' case, the length of an Olympic stadium. Eratosthenes had an assistant ***walk*** the distance between Syrene and Alexandria (the best North American analogy would be between Cabo San Lucas and Ensenada in Baja California). The distance thus obtained was 5,000 states. Now an angle of 6 degrees is 1/50th of a complete circle of 360 degrees. The distance between Alexandria and Syene must therefore be 1/50th of the earth's circumference. Thus

Circumference = 50 x 5,000 = 250,000 stade

There has always been some disagreement over exactly how to convert *stade* into modern units, but many scholars have settled on 148.8 meters per stade. Using this number, Eratosthenes' figure translates to 37,200 km or 23,250 miles, very close to the modern value of 25,000 miles.

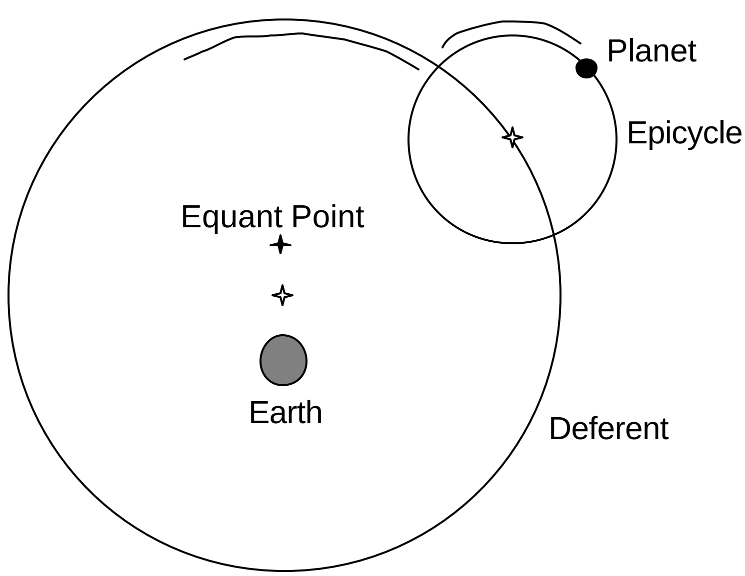


Hipparchus (190 B.C. – 120 B.C.)

Hipparchus of Nicaea is considered the most accomplished observer of ancient times. He is credited with preparing the ancient world's most accurate star map and catalog of stars visible to the naked eye and with discovering ***precession***, the slow shift of position of the stars on the celestial sphere (explained today as due to a slight wobble of the earth's axis). He also made careful observations of the moon that enabled him to correct Aristarchus' figures for the moon's distance and size to something very close to their modern values (moon distance, about 60 earth radii; moon diameter, about 1/4 earth's). Hipparchus' map was so accurate that Edmond Halley nearly 2,000 years later could deduce, by comparing the positions of stars in his day with the ancient map, that the "fixed" stars were not fixed at all, but moved slowly amongst themselves on the celestial sphere.

Ptolemy (100 A.D. – 170 A.D.)

Claudius Ptolemy, from Alexandria like Eratosthenes, summarized the ancient world's understanding of the universe. He his best known for his geocentric model of the solar system which was sufficiently detailed that positions of the planets could be predicted into the future with reasonable accuracy. To account for retrograde motion, he used a smaller circle (the ***epicycle***) moving on a larger circle (the ***deferent***). Ptolemy did not invent this system (the concept is usually credited to ***Apollonius*** of Perga (240 – 120 B.C.)), but Ptolemy added features that made the system work remarkably well. It was all explained in a book known in medieval Europe by its Arab name, ***The Almagest,*** and was taken as the last word in mathematical astronomy by scholars for the next 1,400 years. A simplified version is shown below:



The motion of a planet around its epicycle, which is in turn moving around the deferent, will trace out a loop, simulating retrograde motion. The earth is offset from the center of the deferent so that a planet will appear to move at different rates as seen from the earth, but will move at a uniform rate with respect to the ***equant point***. The earth and the equant point are equally spaced on opposite sides of the deferent's center. Using this stratagem, Ptolemy believed that he had satisfied Plato's and Aristotle's requirement that heavenly motion must be both perfectly circular and uniform. The observational fact that the motions of real planets have neither of these attributes is an illusion which arises from our earth bound perspective.

Knowledge of the Universe at the End of Classical Antiquity

1. The earth is a sphere *(Pythagoras, Aristotle, Ptolemy)*
2. The diameter of the earth is approximately 8,000 miles *(Eratosthenes)*
3. The moon shines by reflected light of the sun; solar eclipses are due to the moon covering the sun, while lunar eclipses are due to the earth's shadow covering the moon. (*Anaxagoras*)
4. The diameter of the moon is approximately 1/4 the diameter of the earth (i.e.~2,000 miles) *(Aristarchus, Hipparchus)*
5. The moon is approximately 60 earth radii away (~240,000 miles) *(Aristarchus, Hipparchus)*
6. The Sun is very far away (20 times the distance to the moon) *(Aristarchus)*. *The number is wrong, but it suggests that the solar system is very large.*
7. The Sun is very large compared to both the moon and the earth (20 times the moon, 6 times the earth). *(Aristarchus)* Again, the w*rong figure, but* *<u>qualitatively</u>* *correct*.
8. The earth is very small compared to the universe ("as a point when compared to the celestial sphere"). *(Aristotle, Ptolemy)*
9. The "equinoxes" (the intersection between the ecliptic and the celestial equator) are *<u>precessing</u>* (slowly changing position). *(Hipparchus)*

Models of the Universe

1. Aristotle***:*** ***geocentric*** (earth in center) with nested spheres, one or more for each planet
2. Ptolemy: ***geocentric*** with planets moving on *epicycles* and *deferents*. (small circle (epicycle) moving on large circle (deferent)).
3. Aristarchus: ***heliocentric*** (sun in the center) with the earth as one of the planets revolving around the sun.