Chapter 3:
The Greeks:
Triumph of Rational Thought and Mathematics

The long era of Greek *Philosophy* (literally, "love of wisdom") began in the early seventh century B.C. (Table 3.1). The concept of "science" as an organized view of the world (expressed by the Greek concept, "Cosmos") arose alongside mythology as an alternate way of viewing and interpreting nature. The two parallel ideals developed and prospered together for several centuries, neither entirely supplanting the other. The relationship, however, was not always amicable. Suspicions regarding the irreligious attitudes of the philosophers in the later years of the fifth century led to the condemnation and banishment of Anaxagoras from Athens, the execution of Socrates, and impassioned attacks against Aristotle, among other episodes of intolerance.

The world of Geek mythology as brought down to us by Homer in the *Iliad* and the *Odyssey*, and by Hesiod's *Theogeny*, was a fanciful world of anthropomorphic deities (Zeus, Hera, Hades, Athena, etc.) who purposely affected human affairs for both good, mischievous, and evil outcomes. It was a world of chance in which capricious spirits could wend their magic on hapless humans in the time and place of their choosing. Casting predictions of future events in such a system is prone to be a wasted effort. Of course Homer and Hesiod, and those sage souls before them, were intent on addressing questions of causation mostly to instruct and entertain. Mythology was never sold to the populace as an empirical science.

On the other hand, *science* – as we define it today -- was born and given shape and form during the age of the Greek philosophers. Modern students should be cautioned not underestimate their profound contributions to scientific understanding.

Thales of Miletus

Two “schools of thought” arose during the Grecian philosophical era. These competing groups were: the *Ionians* -- a group of great thinkers, most of whom lived on islands or coastal city states scattered along the east coast of the Aegean Sea, an area of Asia Minor now administered by Turkey (Fig. X) – and the *Mainland Greeks* who lived in large city states like Athens. The Ionians produced the first great Greek philosopher, Thales (pron: Th-all-es) of Miletus.

Miletus stood in the middle of a swampy deltaic flood plain at the mouth of the Meander river (from which the term *meander* is derived). In Thales’ time it was a center of maritime trade, sporting no fewer that four separate harbors. It was here around 640 B.C. that the mutiny against superstition and fuzzy thinking took root with the birth of Thales, commonly accorded the honor of being the world’s first scientist. Thales claimed that human reason could be applied to questions regarding the nature and origins of natural phenomena; the gods of Olympus were of no help in that endeavor. In his time his Greek contemporaries deemed him one of the Seven Sages, the seven wisest men on earth.

Thales was a wealthy merchant (in a town awash with them), which allowed him considerable latitude to travel and study. He had an insatiable thirst for learning and an intense curiosity about the natural world. He traveled to Babylon (Chapt. 2) for the purpose of acquiring their knowledge of astronomy and mathematics, and the historian Herodotus noted that he gained lasting fame by predicting a solar eclipse in 585 B.C. However, that tale is likely an exaggeration considering that the requisite knowledge and techniques for that feat were not developed until many hundreds of years in the future.

Thales also spent considerable time in Egypt. He stunned the Egyptians with his ability to measure the height of the pyramids by applying the law of similar triangles, and was celebrated for his ability to measure the shoreline distance of a ship in the Mediterranean Sea. His mathematical prowess was such that he laid much of the groundwork for the great mathematician Euclid, who lived centuries later. He is credited with the first system of logical reasoning, and he coined the word *geometry*, Greek for “earth measurement”, the terminology he learned from the Egyptians.

Perhaps Thales’ greatest contributions to modern science – and astronomy – are the notions that **all natural phenomena can be understood via reason and observation**, and the idea that **nature follows regular laws**. He firmly rejected the intercession of the gods in creating natural materials or events. These concepts are the underpinnings of what is now popularly termed the “scientific method”.

In an amazing leap of intuition, he also explored the ultimate nature of matter and space. He speculated that despite apparent differences, all matter must be composed of a single, fundamental material (anticipating the concept of atoms). Thales is commonly derided for assuming that this fundamental material essence was, in fact, water, but living in a watery world no doubt lead him to that “logical” conclusion. His notion that the earth is a flat disc floating on water, however, does illustrate the limitations of some of his cosmological constructs.

In his declining years, Thales met with Pythagoras and is known to have been a profound influence on the young genius. His parting advice to Pythagoras was to visit Egypt to expand his knowledge of nature, a suggestion he later followed. Pythagoras is said to have paid homage to his visionary mentor by singing songs of praise about Thales during solitary times at home.

Pythagoras of Samos

Most people know Pythagoras for the geometric theorem involving right triangles that bears his name. Impressive as that was, it stands as only one of his many contributions to science. His mathematical and scientific prowess far surpassed the great sage Thales. Ultimately Pythagoras amassed a considerable body of work and attracted a devoted cadre of disciples who carried on his work and spread his philosophy for many years after his death.

Pythagoras began his life about 580 B.C. in the city state of Samos, on an island of the same name off the coast of Asia Minor near Miletus. At age eighteen, upon the death of his father, his uncle adopted him. This uncle later sent him off to commune with the great philosopher Pherecydes on the island of Lesbos. The significance of this encounter is that Pythagoras acquired from Pherecydes an introduction to the Phoenician concept of the immortality of the soul and reincarnation. He would later incorporate those ideas into a religious doctrine that also included such tenets as the sinfulness of eating beans.

Eventually Pythagoras did venture forth to Egypt as Thales had suggested, but what he encountered there disappointed him. The Egyptians saw mathematics as a purely practical tool, useful for measuring property or field boundaries, or calculating the height of a pyramid. The genius of Pythagoras was that he envisioned a new, more imaginative mathematics, that space can be represented as a mathematical abstraction. Mathematical concepts like lines and planes didn't have to represent a fixed material object like a fencerow or face of a building stone, but could apply to a variety of situations. In other words, the uses of mathematics were virtually limitless.

One of the first problems Pythagoras is said to have investigated with his revolutionary mathematical regime was the relationship between the length of a vibrating string to the pitch of the musical note it produces (short strings sound higher). The discovery of this relationship is assumed to represent the first empirical discovery of a natural law. His "law of harmonics" was to influence much later ideas relating the motions of heavenly bodies to musical notes, such as "the music of the spheres" concocted by certain Renaissance scientists. Johannes Kepler, as we shall see, was one of the most prominent advocates of the influence of harmonic tones to celestial motion. Plato also relied heavily on Pythagorean principles in formulating the geometric aspects of his cosmology. Aristotle owed his knowledge of a spherical earth (which he proved empirically) to the theoretical musings of Pythagoras, who envisioned a spherical earth based entirely on aesthetic geometrical principles.

The principal contribution of Pythagoras to science was the concept that **natural phenomena can be described by mathematics**. In fact, he and his followers were disdainful of any pursuit of knowledge that was devoid of mathematical analysis. In their rigid philosophy, all of nature could be reduced to a harmonious state of mathematical first principles. Most modern physicists and astronomers would offer little argument with that view.

But Pythagoras' philosophy was not without some warts. As a manifestation of his religious domain, he held many mystical numerological beliefs. He gave us the concept of even and odd numbers, but associated odd numbers with masculinity and even numbers with feminine qualities. He also associated certain numbers with various social concepts; the number 1 was reason, 2 was opinion, 4 was justice, and so on. Because squares are four-sided figures, we use the expression "square deal" today to signify a just situation. However, these diversions from rational analysis cannot tarnish the profound accomplishments of Pythagoras and his students, nor diminish their immense importance to the development of science and mathematics.

Anaximander, Student of Thales

Like Thales, Anaximander was a resident of Miletus, although very little is known about his life. Most of what we know about him was handed down from Aristotle and his student Theophrastus. He was probably a student, or at least an important contemporary of Thales, founded a colony on the Black Sea (Apollonia), and introduced the gnomon-style sundial to Greece. He was a seasoned traveler and besides astronomy, also contributed to the study of geography and biology. For instance, Anaximander is credited with producing the first major world map (550 B.C.), and speculated that life evolved from lower forms of life, in a very primitive precursor to evolutionary theory. Humans, for example, evolved from fish, which constituted the first animals. Remember, like Thales, Anaximander lived in a world dominated by water.

Perhaps his most profound contribution to astronomy is the "Boundless" principle, known as *apeiron* in Greek. The *apeiron* was a highly abstract concept but contained the idea of "that which has no boundaries", a system without limits. It was philosophically at variance with Pythagorean virtues of a harmonious, symmetrical, and finite world, reassuringly accessible and knowable through mathematics. In fact the Pythagoreans listed the *apeiron* concept as a "negative thing", and Aristotle is known to have been troubled by its lack of limits. The "Boundless" seems to embrace the infinite, and somewhat parallels our current overall concepts of the nature of the universe.

Anaximander was not content to simply propose an abstract concept like *apeiron* without presenting logical arguments in its defense. In that respect he seems to be the first Greek to make use of true philosophical argument, an important step toward the systematic, rational analysis of nature embodied in modern science.

Anaximander was not an observational astronomer like the Babylonians and Egyptians, but a speculative astronomer. He relied on pure reason and logical arguments to prove his points, a situation in keeping with the teachings of Thales. For example, Anaximander speculated that (1) celestial bodies make full circles and may pass beneath the earth, (2) the earth is a free-floating body in space, and (3) celestial bodies may lie behind one another (not "painted" on a two-dimensional surface).

As for the "Boundless" concept, he offered logical arguments for each speculation, and for each he should be awarded a gold star for accuracy. Interestingly, his argument for a suspected earth includes the notion of the centrality of the earth compared to the rest of the universe. Since all things should seek that central point, that which occupies that space must hang suspended. Interesting philosophical argument, even though the science lacks some rigor. Gravity and the non-centrality of the earth were still distant ideas in his day.

One of Anaximander's more bazaar astronomical speculations was his idea that celestial bodies were generated as points of light streaming from holes in fire-filled tubes (chariot wheels) that encircled the earth. The sun, moon, and stars were all explained by various size luminous holes in wheels composed of "opaque vapor". The wheels, although ostensibly a strange concept, were contrived to solve the "falling" problem of bodies suspended in space. By circling the earth (as per every-day observation) attached to wheels, the bodies were prevented from falling pal mal into the earth. Unfortunately, this idea persisted well into the future, helping to span the various crystalline spheres or ethereal sphere-shells theories of attaching non-free-floating bodies to the celestial dome.

Anaxagoras of Clazomenae

Anaxagoras was born about 500 B.C. into a wealthy family in the Ionian neighborhood of Smyrna, now Turkey. His work was described by Proclus, the last major Greek philosopher (c. 450 A.D.). He fully embodied and embraced the spirit of Ionian philosophy, evidenced by his early abandonment of possessions and wealth in pursuit of the study of science and mathematics.

Anaxagoras overlapped and lived after the time of Pythagoras and greatly expanded upon his mathematical cannon. About 480 B.C. he moved to Athens and is given credit with first introducing the Athenians to Ionian ideas. Unfortunately, Anaxagoras later met with some difficulties with the state authorities after assuming an "intimate" relationship with the great political and military leader of Athens, Pericles. In about 450, he was imprisoned by Pericles' political opponents for claiming that **the sun was not a god (it was a "red-hot stone"), and that the moon shines by reflected light.** Although later released and exiled, the reasons given for his imprisonment are revealing:

he had violated a law allowing for prosecution of any Athenian citizen (or foreigner) who did not practice religion and taught theories about “the things on high”.

Anaxagoras used his knowledge of geometry to offer the first accurate explanation for both solar and lunar eclipses, and also developed a model for solar system evolution not improved upon for over two thousand years. The latter model involved a spinning “vortex” that flings materials outward from a central origin (anticipating the Newtonian concept of *centrifugal force*). In the process, materials of differing composition defined as *aether* (hot dry air), water, and earth (stones), separated from one another to be distributed in various regions arranged about the center. During this process, heavy matter accumulated in the center as earth. The outward ejection of fiery *aether* produced hot stones from the earth that became stars.

Anaxagoras postulated that this “vortex” mechanism was set up by something called *nous*. *Nous* was translated as “mind” or “reason”. Initially, according to this concept, all things were together, matter was a homogeneous mixture. It was *nous* that created the conditions (the vortex) by which matter could separate into its essential “elements” (a term coined later by Plato). It is not hard to recognize in this concept, the four natural elements – earth, fire, water, and air – expounded upon by Empedocles (a contemporary of Anaxagoras), and advanced later, somewhat modified, by Plato and Aristotle.

Anaxagoras also dabbled in biology, suggesting that *nous*, the power of mind, not only created the world, but also controlled the growth of living things. Organisms used *nous* to coax nourishment from ingested matter. Note that *nous* can also be defined as “divine mind”, suggesting that Anaxagoras may not have divorced himself entirely from the concept of a “spiritual force” initiating the universe. Yet his ideas do not postulate the intercession of anthropomorphic gods such as Zeus. As a strict Ionian, he probably saw *nous* as a natural force, the *dominant* natural force.

After exile from Athens, Anaxagoras returned to Ionia where he founded a school at the Greek city of Lampsacus, Mysia on the Hellespont (strait between the Sea of Marmara and the Aegean Sea). Before he died (428 B.C.) he purportedly was asked, “What is the point of being born?” He is alleged to have replied, “ The investigation of the sun, moon, and heaven.”

Plato and Aristotle of Athens

At this point, we will temporarily leave the Ionians and journey back in time and space to Athens, home of two of the greatest and most famous of Greek philosophers, Plato (427 to 347 B.C.) and his student, Aristotle (384-322 B.C.). Although much of their scientific work has been largely discredited, they established for all time the methods and intellectual framework necessary to scientific research as practiced today.

Plato was a nickname given to this athletic youth by his coach because of his broad shoulders. His real name was *Aristokles*. He is well known for establishing his Academy of Athens, where elite, future leaders of Athens were instructed in the “liberal arts”, philosophy, ethics, mathematics, natural science, and what we might call political science. The methods of rational discourse employed at the Academy were derived from Plato’s mentor Socrates. They included dialectic analysis involving the formulation of a series of questions and answers. They also made use of the revolutionary Socratic idea of “deductive” reasoning, i.e., formulating a hypothesis to explain some natural phenomenon, then providing proof to support the hypothesis. It is commonly used along with "inductive" reasoning (using observations and experimentation to formulate a working hypothesis) as the guiding framework of modern scientific investigation.

Influenced by the work of Pythagoras, Plato emphasized the orderly, symmetrical aspects of nature. One of his favorite discussion topics with his pupils was the geometry of the five perfect solids. In a perfect solid all planar faces are the same shape everywhere and the sides are of equal length (square, equilateral triangle, pentagon, etc.). Angles connecting the faces are similarly all equal. One hundred years later, Euclid showed that it is mathematically possible to construct only five perfect solids., the cube, tetrahedron , octahedron, icosahedron, and dodecahedron. Plato used this idea to support the concept of the five elements that comprise the physical world, earth, water, air, fire, and ether (heavenly medium).

Like Pythagoras, Plato was prone to attach human qualities, like justice and virtue, to mathematical forms. But he took a step further by proclaiming that the cosmos could be split into two realms, that of "form" and that of "substance". The world of form included pure Socratic ideals such as truth and beauty, or perfect symmetrical geometric constructs imagined by mathematicians (e.g., the five perfect solids). Substance was the real world of the ever-changing earth with its imperfection and decay. Through this philosophy he set forth the prefect square or, especially, the prefect circle as concepts rarely found in nature, but easily conceived and contemplated in the mind. The grand consequence of this duality of form and substance is that it is only "the domain of universal ideals that is truly meaningful". The familiar world of physical matter was just an illusion. Our senses lie (a spherical earth appears flat), so true reality can only be grasped by the mind. Observations fail to reveal the true essence of existence.

Thus Plato counseled his students to not waste their time observing nature, but to contemplate it with their minds instead. Unfortunately, the first part of that edict is a profound mistake, and has earned Plato something of a black eye with modern scientists. Also, his devotion to the ideal form of the perfect circle for reasons of aesthetics, religion, and tradition caused that form to endure in future models of planetary motion, despite the problems it posed to precise prediction. It wasn't until Kepler – nearly two thousand years later -- that elliptical planetary orbits were found to actually fit physical reality, a blemish on the heavens Plato would have found abhorrent.

Plato, along with his younger contemporary Eudoxus of Cnidus (ca. 390-ca. 337 B.C.) did make strides toward our understanding of planetary motions, laying the groundwork for many future studies. For one thing, they were instrumental in shifting emphasis away from purely stellar concerns toward the study of planetary, lunar, and solar motions. The motion models they produced were ingenuous, and although lacking precision in predictive power, they mirrored reality more closely than previous models.

Their first attempt was the "Two-sphere" model of the cosmos (Fig. X). Exchange the earth for the sun in this model (and vice-versa) and its appearance closely resembles illustrations in modern astronomy texts. It consisted of the sphere of the earth enclosed by a much larger sphere to which are affixed the sun, moon, planets and stars. This sphere rotates east to west, once around every day to account for what we call the diurnal (24 hour) motions of the heavenly bodies across the sky. The sun, moon and planets move west to east along the surface of the outer sphere along the ecliptic, which is angled at 23 degrees to the celestial equator (projection of the equator into space).

Actual movements of sun, moon, and planets had been measured and were well known by the time of Plato, so the model shows the sun making one orbit around the ecliptic ina year, the moon performing the same journey in one month. It was also recognized that the planet Mars would take far less time to make one orbit (687 days) compared to planets like Jupiter (about 12 years). In addition, the location of the spring and fall equinoxes could be shown where the ecliptic intersects the celestial equator, and the two solstices were shown as the highest (summer) or lowest (winter) point in the sun's path compared to the equator.

However, as successful as the two-sphere model was in giving a general impression of heavenly motions, it was less successful as a genuine tool for predicting where a body might appear at a particular time of the year – or in future years. Nor was it successful in accounting for the apparent backward motion shown by all planets called retrograde motion. The model also failed to explain why some planets, namely Venus and Mercury, were never found far from the sun, but either leading it or following close behind.

To remedy this situation, Plato is said to have issued a call to all working astronomers and mathematicians to develop a model to determine what combination of uniform circular motions could account for the seemingly capricious motions of planets. The first to answer the challenge was Eudoxus who, having worked on the original model, had something of a head start on the others. Eudoxus contrived several mathematical models that had in common the idea of "nested spheres", multiple spheres controlling the motion of a single planet, each sphere rotating in different directions and speeds in order to simulate observations. He inserted a figure-eight figure called a "hippopede" in a later model just to account for retrograde motion (planets commonly appear to produce a figure-eight during retrograde motion) and continued to tinker with the number and rotation attributes of spheres in order to fine-tune the model. A good question to ask is whether or not Eudoxus actually believed that his models conformed to actual physical reality, or were mere mathematical constructs. In fact, little evidence exists that Eudoxus actually believed his models represented physical reality; he did not think that the planets were controlled by real interconnected moving spheres. His greatest interest was in finding mathematic order.

A generation after Eudoxus, Callipus of Cyzicus (b. ca. 370) made various improvements on the nested sphere model, mostly by adding more spheres and adjusting motion proscriptions for the various bodies. Aristotle took the Callipus model a giant leap forward by considering how the motions of planetary spheres might affect the motions of other planets. By the time he had the whole thing figured out to his satisfaction, he had constructed a monster consisting of fifty-five planetary spheres plus one for the fixed stars!

Of greater importance, however, -- beyond the accuracy of Aristotle's model – was his personal attitude toward it. Unlike Eudoxus (and probably, Callipus), Aristotle came to see his model as an actual representation of reality. He concluded that multiple nested spheres would be required to explain the motions of the heavenly bodies, and to hold them in place. Otherwise, there would be nothing to prevent the planets, moon, sun, stars and all the rest of heavenly creation from crashing down on the earth as they sought their rightful place at the earth's center (see below). Because Renaissance scientists relied on Aristotle as an important primary source of scientific wisdom, many of them apparently viewed the concept of "crystalline" or celestial spheres as real and essential properties of the heavens. Tycho Brahe, for example, was able to show that the celestial spheres did not exist because a comet he observed in 1577 passed through them unimpeded.

After his mentor Plato died in about 347, Aristotle spent several years traveling about the Aegean Sea, including spending time in Ionia where he pursued his various biological studies. He eventually settled in his native Macedonia where he was appointed to be young Alexander's (the Great) tutor by his father Philip. In 355 Athens fell under Macedonian rule whereupon Aristotle returned to found his school in a garden meeting place called the Lyceum. He is credited with writing some 150 treatises, whereas only thirty remain today. However, like Anaxagoras earlier, he was eventually chased out of Athens on pain of death for lack of proper piety and respect for the gods.

Whereas Plato turned his head to the heavens seeking ideal perfection, Aristotle's main interests lay in the practical problems of the earthly realm. He tackled some of the fundamental problems of physics like the nature of motion, and the tendency of objects to fall toward the earth, a quality he attributed to an intrinsic property of matter that he termed *gravitus*. We will return to these studies below, but first we shall examine one of Aristotle's great successes as a means of showing how he approached a scientific problem.

This problem was to prove the Pythagorean notion that the earth is spherical, rather than flat as proposed by Thales and others. Aristotle is commonly denigrated by modern writers for sloppy thinking, or for his "unscientific" conclusions and grand unproven postulates of nature. However, the methods used by Aristotle generally fit his purposes and were appropriate to the scale of his inquiries, and to the instrumentation and knowledge of the times. For example, to prove the hypothesis that the earth is a sphere, he offered three empirical observations: (1) the shape of the shadow of the earth projected on the moon during a lunar eclipse is curved; (2) ships seen to gradually disappear over an horizon do so gradually, hull first followed by the mast; and (3) travelers traversing north or south on the earth's surface commonly report seeing new constellations in the direction of travel, and the loss of familiar constellations in the direction of departure. All three observations would be impossible given a flat earth. Case closed; proposition verified.

In some other areas he was somewhat less successful, but given the circumstances his arguments are not entirely outrageous, and may only seem so to us because we have the advantage of hindsight – and Newton. One example pertinent to astronomy is his study of moving bodies.

Aristotle postulated two basic principles, which form the basis of his motion theories: (1) motion is never spontaneous; there is no motion without a "mover", and (2) two types of motion exist, motion toward the "natural place" of the moving body (natural motion) and motion in any other direction (forced or violent motion). The natural place for falling bodies, for example, was the earth's center; any falling body will seek that place. One very important implication of these postulates is that in order for a body to remain in motion, a "mover" (force) must be present at all times, or the body will cease to move. Aristotle also envisioned a "resistance" or opposing force that would tend to retard motion, either slowing an object or stopping it, depending on the strength of the resistance.

Note that Aristotle's motion postulates conform well to everyday experience for an earth-bound observer. However, we can imagine one of his brilliant pupils, say Theophrastus, his longtime student and colleague, asking him why a thrown javelin remains in flight long after it has been unleashed by the throwing arm (the "mover") of an athlete. Aristotle's answer was that after the mover set the object in motion, the medium through which the object moved took over and pushed against the object. If pressed, Aristotle would have added that this "push" was caused by the medium (air, in this case) rushing in to replace a vacuum caused by the passing object. For objects in space the medium acting as surrogate mover is the "ether", the fundamental element occupying the heavens (see below).

Aristotle also considered the special case of falling bodies, as where the javelin eventually falls back to earth. It does so, of course, because it is seeking its natural place, the earth's center. He postulated a law stating that the rapidity of an object's fall was directly proportional to its weight, or *gravitus*, and indirectly proportional to the thickness of the medium through which it fell. Thus, a leaf dropped with a large stone will play the tortoise to the stone's hare and arrive late to the ground. Also, if objects of equal weight fall from the same height, the one that falls through the thickest (most viscous) medium will arrive late compared to the other. One could imagine objects dropped through air versus water as a "thought experiment"; the air provides less resistance, so the airborne object wins every time. These are all perfectly valid observations – on the earth's surface.

Next we should consider Aristotle's views on the nature of matter for how they influenced later scientific thinking, and for what they tell us about Aristotle. Aristotle constructed a cosmology (model of the universe) in which the earth occupied the center, but surrounding earth were other compositionally distinct layers or shells (Fig. X). He considered, with some rational basis, that the layered order should be dictated by the "heaviness" of the constituent "elements". Thus, water constituted the layer above earth, followed by the obviously lighter air, and topped off by an invisible layer of fire. Lightening was explained by a violent discharge of this fire when the layer was disturbed by storms. So the region near the earth was comprised of the four essential elements, earth, water, air, and fire. Aristotle, however, could not imagine an "airless" space (witness his quote, "Nature abhors a vacuum") so, like Plato, he proposed that a fifth substance composed the heavens, "ether". Interestingly, the term and concept persisted as a scientifically accepted fact into the early twentieth century.

It is in his concept of the heavenly realm that Aristotle found it hard or impossible to break with his old master Plato. Aristotle proposed that ether represented a uniquely pure and ideal substance. But ether not only provided the medium in which celestial bodies resided, it also composed the bodies themselves. Thus, the moon, sun, planets, and stars were all composed of ether, rendering them perfect, unblemished, and unchanging over time. Plato could not have stated it better, nor would he have tried.

Unfortunately, neither Aristotle nor his supporters – then, and later during the European Renaissance – had any inclination to test his exquisite theories with controlled experiments, or even simple naked eye observations. The idea that hypotheses, of necessity, require objective verification would not take hold for another two thousand years, and not without considerable struggle.

Aristotelians were content to conjure up some truly imaginative rationalizations for why observations of nature did not always fit their models. For example, if the heavens are regular and inalterable, why does the moon's face possess pox marks, and what causes the sudden appearance of comets with their ever-changing tails and erratic motions? If two rocks of unequal size are dropped from a cliff, do they really fall at different rates? Aristotle proposed answers to these questions, but they were not particularly satisfying, especially to the modern reader. But despite that, he should not be dismissed as an impediment to scientific advancement, or as a fool who got it right at times, but mostly failed miserably. Aristotle's lasting contribution was establishing methods for organized and reasoned analysis of nature, including hypothesis building, modeling, and careful observation. That he sometimes failed to adequately verify his models does not take away from his overall contribution as the father of rational scientific analysis.

Aristarchus of Samos

Little is known about the life of Aristarchus (c. 320-c.250 B.C.), although his contributions to astronomy were revolutionary in that he moved the sun into its rightful place as the central object in the solar system. Drawing on the ideas of Pythagoras and his follower, Philolalus, Aristarchus proposed that the daily motion of the sun and stars across the heavens was caused by the earth's rotation about an axis. He then took the revolutionary step of placing the sun in the center of creation with earth revolving around it like any other planet. This left only the moon to revolve about the earth. With the exception of circular orbits, which he maintained, the planetary model of Aristarchus is a perfect match to the modern heliocentric version.

But Aristarchus went beyond creating the first accurate picture of the solar system. He also devised ingenuous geometric methods for calculating the relative sizes of the sun, moon, and earth, and their distances from one another. Although wildly inaccurate in magnitude, his calculations showed for the first time that the sun was a much larger body than either the earth or moon, and was significantly more distant than previously believed. Before Aristarchus it was assumed that the sun and moon were located at equal distance from the earth, and were of equal size.

To calculate the sun's distance from the earth-moon system, Aristarchus made use of similar triangle analysis (Fig. X). He conjectured that because the sun is a finite distance from earth, its rays must diverge ever so slightly from parallel. This situation would cause a small, but measurable time difference between the new moon and quarter moon phases compared to the quarter moon – full moon time interval. Thus, the moon-earth-sun angle, which would be 90^o for parallel rays (sun at infinite distance), should actually be some angle slightly less than 90. Aristarchus determined this to be 87^o, which by similar triangle analysis leads to a short side-hypotenuse ratio of 1:19. Because the hypotenuse in this analysis represents the earth-sun distance, the sun must be 19 times more distant from earth as the much smaller earth-moon distance (adjacent short side; Fig. X). Unfortunately, Aristarchus lacked a precise clock for measuring the critical time differences between phases that determines the critical angle. The actual difference is about 40 minutes out of 28 days; he measured it at 11 hours! The resulting earth-sun distance is far shorter than the true distance. In fact, the sun is about 430 times more distant than the earth-moon distance, but that need not concern us. Even with that considerable error, Aristarchus could now make the revolutionary claim that the sun was much farther away from us than the moon.

Aristarchus next tackled an even greater challenge, estimating the size of the sun (Fig. X). This measurement was done by applying geometrical analysis to the situation of the total solar eclipse, when the disc of the moon seems to cover that of the sun. By similar triangle analysis, the ratio of the moon/sun sizes is equal to the ratio of the distance. Because the distance had been previously measured at 19 units, the sun must be 19 times as large as the moon. Using data derived from total lunar eclipses (Fig. X), Aristarchus concluded that the sun's diameter is about seven times that of the earth.

We now know that the angle upon which Aristarchus based his measurements was not 87 degrees, but 89 degrees and 50 minutes. The difference seems small but it is enough to throw off the measurements by several orders of magnitude. Nevertheless, his accomplishment in even devising such clever experiments represents a major breakthrough in the quantitative analysis of the heavens.

As a postscript, Aristarchus' contemporaries unanimously rejected his heliocentric model as irrelevant and heretical speculation. For his efforts he was condemned for impiety and exiled him from Samos. For his part, Aristarchus pointed to his size measurements to argue that a large body like the sun would hardly deign to orbit a puny little body like earth. However his critics argued that a moving earth counters all degrees of common sense and everyday observations an, besides, there was the matter of *parallax*. This factor (the word pertains to measuring angles) refers to the apparent movement of distant objects relative to more distant objects as the observer shifts position.

The effect can be simulated by holding a finger at arms length and closing one eye, then observing the finger with only the other eye open. The finger will seem to shift position even though it has actually not moved at all. Repeating the experiment with the finger closer to the face produces an even greater apparent angular shift. Parallax of stars should be observed if nearby stars are observed at different positions of the earth relative to the sun. Aristarchus' critics argued that if the earth actually orbited the sun, its displacement in space should result in measurable stellar parallax. Instruments in Aristarchus' day were highly inadequate for the precision necessary to measure such small apparent shifts in star positions.

So those negative parallax observations – valid in terms of available data -- swung opinion against Aristarchus and his heretical model. In his defense, Aristarchus pointed to his distance measurements and concluded that parallax could not be measured owing to the extreme distances of the stars. He was, in fact, right, but solid evidence -- sufficient to overthrow a long-held, nearly sacred belief in an earth-centered cosmos -- was conspicuously lacking. The heliocentric model was reintroduced to the world nearly fifteen hundred years later by the Renaissance scholar and cleric Nicolaus Copernicus.

Apollonius of Perga and Hipparchus of Rhodes

Rejection of the heliocentric model of Aristarchus left the door open to continued modification and improvement of earth-centered models advanced by Eudoxus and Aristotle. As in the pre-Aristarchus past, astronomers continued to mold the venerable earth-centric systems into reliable tools for predicting planetary motions. Two prominent leaders in that effort were Apollonius (c.262-c.190 B.C.) and Hipparchus (c.170-c.125 B.C.). Of the two, Hipparchus is the most well known, but his work to develop a practical planetary model was greatly influenced by Apollonius.

Apollonius started by throwing out the old nested spheres idea and substituting a much simpler model with each planet moving along a simple circular orbit called a *deferent* (Fig. X). To account for the viable brightness exhibited by planets over time, he removed the earth from the center, offsetting it somewhat to one side. This slight move, considered sacrilegious by some, was certainly far less radical than what Aristarchus had done to the earth's privileged centralized status. Furthermore, it succeeded in showing how variable distance from earth along its orbit (now called an *eccentric*) would produce the observed dimming and brightening of a planet.

Apollonius also devised a neat trick for explaining retrograde motion by introducing the *epicycle*, a small circle riding along the eccentric such that the planet traced out a spiraling pattern as it also moved along its orbital path (Fig. X). His model succeeded, where others had fallen short, in facilitating fairly accurate predictions of planetary motions and positions over time. In the process, Aristotle's 54 rings were relegated to the dust heap, but not for long. Arab scholars and, later, European scholastics revived the nested spheres idea along with the concept of crystalline spheres and all that they implied about the perfection and immutability of the heavens.

We cannot leave Apollonius without mentioning that perhaps his greatest contribution to astronomy (and geometry) was the concept and study of the four "conic sections", the circle, ellipse, parabola, and hyperbola. All these figures can be generated by slicing a cone at various angles. For instance, a slice cut parallel to the base produces a circle. A cut at a slight angle to the first one, produces an ellipse, and so on. Ironically, the ellipse would prove to match the actual orbits of the planets (and their satellites), the discovery of which by Kepler was the basis of his first law of planetary motion. Although we no longer celebrate Apollonius' model of the cosmos, his mathematical accomplishment lives on in the orbits of the planets.

Hipparchus, considered the greatest observational astronomer of ancient times, made several improvements to Apollonius' models, mostly in tweaking their geometrical proportions to reconcile observed versus predicted positions. His work with Apollonius' planetary models alerted him to deficiencies in the methods then being used to measure the positions of celestial objects. To remedy this, he invented new and more precise measuring instruments. He also made significant advancements in trigonometry, the science of computing angles and distances in triangles, enabling him to better interpret data derived from his observations.

From a specially constructed observatory constructed on the Greek island of Rhodes, Hipparchus carefully measured star position until one evening he discovered a star in the zodiacal constellation Scorpio (the scorpion) that did not appear on existent star charts. He concluded that ancient observers, mainly Babylonians, had apparently missed some stars, so he resolved to make his own map of the heavens. In this lifelong, painstaking effort he cataloged all stars visible to the naked eye (about 850 stars) and classified them according to a "dimness scale" of his own invention. This scale assigns numerical values to stars increasing in value with increasing faintness. Luminosity changes from whole number to the next represented a factor of 2.5. Thus the brightest star, Sirius, has a value of –1; the faintest stars Hipparchus could measure had a magnitude of +6. The negative part of the scale is actually a modern addition to a method called the *stellar magnitude scale* that we still use today. On this scale a very bright object like the moon has a value of –13; the sun comes in at a blazing –28.

Through careful observation, Hipparchus also noted that the plane of the Zodiac – the path of the sun through twelve constellations originally designated by the Babylonians – was not a stable feature of the heavens. An inkling that something was amiss came from his noting that the position of the rising sun on the first day of spring had shifted slightly from that reported by the ancients. Originally, at the *vernal equinox* (the onset of spring, when the sun in the ecliptic intersects the equatorial plane) the sun was in the constellation Aries, the ram. Even today this point where the ecliptic and celestial equator intersect is called the *first point in Aries*. Hipparchus noted through careful observation that the sun had since slipped into the constellation Pisces (the fish). His research took him back as far as 6000 B.C. to Egyptian paintings showing the spring sun rising in Gemini (the twins), a full three constellations away from Pisces.

Hipparchus called this phenomenon the *precession of the equinox*, and although he had no explanation to account for it, he is afforded much acclaim for revealing its existence. It took much painstaking work by later observers to realize that the precession of the sun was caused by a circular wobble in earth's rotational axis. We note that the northern axis now points to Polaris, the "pole star", but this has not always been true. In 3000 B.C., for instance, the earth's northern axis pointed toward Thurban, a star in the tail of Draco the Dragon. The rate of precession, the time it takes for one complete circle, is about 26,000 years, as computed by Hipparchus himself.

Brilliant discoveries like the precession of the equinox were achieved by precision and patient observations over many years. Hipparchus made sure that the positions of stars he plotted were accurate and reproducible, that is, once plotted any observer could use Hipparchus' data to pinpoint the position of any star in his massive catalog. He achieved this by inventing a wholly new celestial locating system that used a grid system similar to latitude and longitude on the earth's surface. North-south direction on the celestial sphere was called *declination* and was measured in degrees starting with zero at the celestial equator working up to 90 degrees at the celestial poles. East-west positions were a bit more complicated, but incorporated a quite rational system of measurement based on time. This system, called *right ascension*, consists of 24 hours reflecting the rotation rate of earth. The zero hour point is the first point in Aries mentioned above. As the earth rotates (the ancients would say the celestial sphere rotates) an observer will note that new stars and constellations will appear at a given direction in the sky at each passing hour. Thus, for example, objects appearing on the *meridian* (projection to the horizon of a line passing through the zenith to the north star) will be at one hour right ascension if they appear on the meridian one clock hour after the first point in Aries appeared there. This is repeated through 2 hours, 3 hours and so on, until the first point in Aries appears again on the meridian.

Note that these are fixed positions in the sky, although precession does throw them off over time. Modern astronomers still use Hipparchus' celestial location system, with computers now used to calculate the precession compensation factor needed to locate very distant objects. With Hipparchus' extremely accurate instruments, he could locate a star within an error of only 10 arc minutes. This is the width of a finger at a distance of fifteen feet.

Hipparchus later applied a similar grid system to terrestrial cartographic charts, so is given credit for creating the first system of latitude and longitude on maps. This system was later used and improved upon by Claudius Ptolemy and others.

Eratosthenes of Alexandria

Eratosthenes (276-194 B.C.) lived much of his life in the fabled Mediterranean port city of Alexandria, then the capitol of Egypt. He had been educated at Aristotle's Academy in Athens, and was a contemporary of Apollonius. In Alexandria he was the chief librarian of the Great Library, repository of most of the volumes of ancient wisdom produced by philosophers and other learned scholars up to that time. His detractors, and there were a few, chided him by referring to him as a "*beta*", an insult meaning second best. But Eratosthenes was anything but second best; he proved this beyond debate by becoming the first human to measure the size of the earth, an *alpha*-sized feat if ever there was one.

Because of his access to the vast literature resources of the premier library of the ancient world, Eratosthenes was aware of the latest chronicles and natural observations of note. Poring over these records one day, he came upon a description of a well in Syenne (present day Aswan) the bottom of which, it was reported, was fully illuminated at the onset of the summer solstice. This would mean that the sun at that time was at the *zenith*, the highest possible point from the local horizon. Thus, at that precise time the sun would cast no shadows. This would also indicate that the town of Syenne was located on or near the *tropic of Cancer,* located some 500 miles (measured in *stadia*, about 1 meter) south of Alexandria.

This solstice observation of the Syenne sun at zenith was at odds with observations at Alexandria made on the same day. Obelisks and other pointed vertical objects did cast shadows, albeit very short ones, at Alexandria. What would cause such a discrepancy? Eratosthenes being of a curious bent set about to discover how the angle of sunlight, assumed to represent parallel rays, could vary so much between two points on the earth's surface. His solution to the problem is as simple as it is profoundly eloquent. School children can be taught how to perform the few simple measurements and calculations required.

Eratosthenes soon understood that the unequal sun angles between Syenne and Alexandria were further proof of a spherical earth. From there he used simple geometry to measure the polar circumference of the earth. To do this, he first measured the length of a shadow cast by an obelisk in Alexandra on the day of the solstice. Using triangle geometry (we would use right angle trigonometry) he found that the angle between the sun's rays at its highest point in the sky (local solar noon) and the vertical obelisk was 7 degrees (Fig. X). He also noted that vertical obelisks (or the shaft of a vertical well) at Alexandria and Syenne, if projected below ground would meet at a point at the earth's center. By equivalent angle deductions derived from Euclid, he could show that the central angle formed by the two obelisks was equivalent to the zenith sun angle measured at 7 degrees. Thus, the angle between the two cities subtends an angle of 7 arc degrees (Fig. X).

Knowing the angular distance between the two cities was key to calculating the whole earth circumference. Because the angular circumference of the earth (or any circle) is 360 degrees, Eratosthenes realized that the whole earth circumference must be $360^{o} / 7^{o}$, or 51.4 times the horizontal distance from Syenne to Alexandria measured in *stadia*. Multiplying this factor by that distance gives a circumference of about 25,000 miles (40,000 km), a result varying only 1.5 percent from the modern value! This makes the earth about a million times the scale of a human being, and goes far toward explaining why the earth appears flat to us puny humans. From the circumference it was an easy task to calculate the earth's radius from the well-known relationship between circumference and radius, $C=2\pi r$.

In truth, Eratosthenes revolutionary measurement contained some significant data errors and faulty assumptions. For one, Syenne (Aswan) was not due south of Alexandria, so the circumference measured was not a true "great circle", one that projects to the earth's center. Only great circles represent the maximum circumference of a sphere. In addition, the Alexandria-Syenne distance, calculated by how long army troops took to march from one city to the other, was probably inaccurate. Furthermore, Syene does not lie on the tropic of Cancer, or even in the tropical zone south of it. The sun cannot appear at the zenith anywhere north of the tropic of *Cancer*, or south of *Capricorn*. But present- day Aswan is well north of the tropic of *Cancer*. Even allowing for some drift of the position of this latitude line since ancient times (caused by slight variation in the earth's orbital tilt), it is unlikely that a sunlit well ever existed in Syene at the solstice, or any other time. Apparently, the many errors in the data simple cancelled out resulting a fortuitous, but remarkably accurate calculated circumference.

It has been recorded that had Columbus used globes constructed from Eratosthenes' measurements, instead of smaller Renaissance-era globes showing the continents to be closer to each other than in reality, he may never have attempted his trans-oceanic voyages. It should be noted, however, that contrary to conventional wisdom, most learned people of Columbus' time were well aware that the earth was round, not flat. Arab scholars had passed this knowledge on to them, having preserved surviving Greek works during the dark ages. Proof of a round earth provided by Aristotle and Eratosthenes certainly would have been widely accepted.

Claudius Ptolemy of Alexandria

Following the work of Hipparchus in the second century B.C., observational and analytical astronomy languished, with most authors preferring to extol the virtues of ancient astronomical practitioners rather than adding anything new themselves. Enter Claudius Ptolemy (c.90-170), a Hellenized Egyptian living in Alexandria. Like Eratosthenes, he directed the Great Library of Alexandria and, while there, rekindled inquiry based observation of the heavens. Ptolemy was not related to the line of Egyptian kings of the same name, but was probably named after a neighborhood in Alexandria bearing that name. This suggests that he was likely born and raised in Alexandria, and not an immigrant from some purely Greek enclave.

Without question, Ptolemy's greatest accomplishment was the publication of a thirteen-volume work that he called "the Mathematical Collection" (*Megale Sytaxis)*, but has come down to us by the Arabic name, *Almagest*, which means "the greatest". In it he summarized the great body of Greek scientific knowledge accumulated over some five hundred years. This book dominated Western scientific thought until the time of Copernicus fourteen centuries later. The *Almagest* was recently re-published as a single volume (see Bibliography), and anyone reviewing its contents cannot help but marvel at the mathematical and geometrical genius behind its many detailed diagrams, charts, and tables. Among other things, Ptolemy's great work contains detailed models containing improvements over the celestial motion models of Hipparchus. He also provided distance and size measurements for the sun and moon, a catalog of 1028 stars (begun by Hipparchus) and descriptions of instruments for observing them, and an improved computation of π (377/120 = 3.1417).

Ptolemy was inspired to modify the motion models of Apollonius and Hipparchus by analyzing planetary observations he made at an observatory in Canopus (named for the star). He noticed many inconsistencies between observed and predicted motions, so set about tinkering with existent models, eventually adding components that greatly improved predictive accuracy. His major innovation was the *equant* (Fig. X), a point situated along the line connecting earth and the center of the deferent, but on the opposite side of the center compared to earth. The equant had the interesting property that the velocity of planets about it was uniform. Thus, a given planet would traverse a given angular distance relative to the equant over a constant period of time. This innovation caused many discrepancies in observed versus predicted planetary motions to disappear, but also introduced profound complexity to the model. To make the model useable, Ptolemy had to construct a separate model for each heavenly body with no connection inferred between them. He ended up with no fewer than eighty circles and epicycles for seven heavenly bodies, far more complex than the fifty-four spheres of Aristotle.

Ptolemy's system was sufficiently accurate that it was used well into Renaissance times to calculate planetary positions useful to calendars and astrological use. But to attain that accuracy – and maintain circular orbits – it morphed into a hopelessly complicated tangle of interconnected circles, angles, and connecting lines wholly unrepresentative of reality. It clearly violated the scientific dictum of *Ockham's razor* (named for William of Ockham 1285-1349) that states, in short, simplicity in scientific explanation is preferred over complexity. It remained for Copernicus to simplify the system by moving the sun back to the center where Aristarchus had placed it, and for Kepler to add the finishing touch, elliptical orbits.

Ptolemy's other major contribution was calculating the relative sizes of planets and their distances from earth, expressed in terms of the earth's radii (obtained from Eratosthenes). He estimated that the moon was some 64 earth-radii from earth, surprisingly close to the modern value (65.5). He noted that Saturn at the outer limits of the known universe was some 20,000 earth-radii away; it's actually just over 224,000 earth-radii distant. Ptolemy's underestimate of the overall size of the cosmos influenced his ultimate rejection of Aristarchus' heliocentric model in that, as he noted, significant parallax distortion of star positions should be observed from summer to winter, if the earth moved. The lack of this parallax, the result of stars being considerably distant compared to his estimates, was enough to condemn the heliocentric model to rejection and ridicule.

Besides his astronomical passions, Ptolemy was also a great innovator in the realm of geography. He wrote a book aptly titled *Geographia* in which, among other things, he improved upon the latitude and longitude system of Hipparchus and Eratosthenes. He showed how latitude (north-south position) can be determined at night using the pole star (angle of the star from the local horizon), and can be determined during the day using the sun's maximum elevation with reference to the calendar date.

Longitude (east-west position) is a more difficult problem, but Ptolemy was up to the task. He pointed out that the sun takes one hour to traverse fifteen degrees. Knowing the difference in sun time from one point to a point east or west gives the difference in longitude between locations. The problem has always been the accuracy of the timepiece used to keep track of the time at the departure point, particularly on ships at sea with their pitching decks and humid, salt air environments, Local noon on ships was easy to measure by establishing the time of the maximum sun elevation, but in ancient time sand-filled hour glasses were used to measure port time, a very inaccurate solution. It was not until the 18th century when the Englishman John Harrison invented the mechanical marine chronometer that sailors could be sure of their precise longitude.

The Decline of Greek Learning

The fate of the Great Library at Alexandria serves as an icon for the decline of Grecian abstract mathematics and science, as the Roman Empire enveloped and absorbed the Greek world. Some two hundred years before the age of Julius Caesar, the Ptolemaic dynasty had begun to decline, culminating in a struggle for control of Egypt by the daughter and son of Ptolemy XII. The daughter was the great Cleopatra who. fearing she was losing control to her brother, appealed to Caesar to step in on her behalf. Caesar did so with gusto, but in the process of battling a mob of Cleopatra's enemies, he found himself trapped in the royal palace where resided the Great Library. Feeling threatened, Caesar ordered that fires be set to ward off the mobs. However, the fire spread to adjacent buildings, including the Library, causing significant damage. This incident represents the first recorded episode of at least partial damage to the Alexandrian Library and its precious cache of scrolls.

Back in Rome, Julius Caesar was later murdered, stabbed in the Theatre of Pompey by twenty-three senators in 44 B.C. Following his death, Alexandria and all of Egypt eventually came under the rule of Octavian, Caesar's adopted great nephew (later known as Augustus Caesar). Octavian took full control after the sea battle of Actium in which Cleopatra and Marc Antony were defeated by Octavian's naval forces. We know that the Library was still operational (in spite of the earlier fire damage) before Cleopatra and her lover's demise. Antony is reported to have donated some 200,000 volumes from the library at Pergamon to the Alexandria Library as a gift to Cleopatra.

As the Roman Empire continued to expand, subsequent emperors had to deal with many practical problems of engineering, architecture, and military tactics but seemed uninterested in furthering the innovative work of Greek philosophers and mathematicians. No Roman equivalent of an Anaxagoras, Pythagoras, or Euclid ever emerged during the nearly twelve hundred years of the Republic and Western Empire.

Roman mathematics, for example, was geared more toward solving specific military problems, than in developing a general theory of the motion of heavenly bodies.

Meanwhile, the Great Library in Alexandria continued in existence under several Roman emperors. Claudius (reigned 41-54 A.D.) is known to have enlarged it with an addition. However, later emperors began choosing directors who were political appointees, beaurocrats who were more interested in the prestige of the position rather than adding to the existing knowledge base, or to the physical collection. Particularly with the rise in Christian influence in Rome, new books appeared that advocated regressive and long abandoned ideas, such as *Topographia Christiana*, written by a Roman of Alexandria. In it he proposed that the earth is flat and that… "the inhabited portion has the shape of a rectangle whose length is double its width." It remained a popular book well into the twelfth century.

The last great scholar to reside at the Library was Hypatia, the brilliant daughter of a great Greek philosopher and mathematician named Theon. She was born around 370 A.D., about one hundred years before the fall of the Western empire. Hypatia later studied in Athens and far surpassed he father in her output of scholarly works, including commentaries on Apollonius' *Conic Sections* and Diophantus' *Arithmetica*. She became a confidant of the Roman prefect of Alexandria, Orestes, but this friendship caused friction with his enemy Cyril, the Christian archbishop. Cyril felt threatened by Hypatia, whose disciples held many high positions within the government and in Alexandrian society. He eventually convinced his followers that she was a witch who was guilty of casting evil spells over the city.

Despite threats to her life, Hypatia bravely continued to give highly attended lectures at the Library. However, as she arrived for one of these lectures one day, she was forcibly pulled from her chariot by a mob of Cyril's supporters, dragged to a church and brutally murdered. They then destroyed her many works, and later burned what was left of the Library. Earlier, in 390 A.D., it had been attacked and nearly destroyed by Christian rioters, who bore resentments against Jews and Greek Neoplatonists. Even before that, much of its collection had been destroyed in 270 A.D. during an attempt by the Emperor Aurelian to suppress a rebellion.

The death of Hypatia and the final destruction of the Great Library at Alexandria marked the end of the era of Greek intellectual innovation. In the Western world, true intellectual pursuits were abandoned to dogma and reverence for "received wisdom", mostly of an ecclesiastical nature. The long period of darkness had begun.

Bibliography

Aaboe, Asger (2001) *Episodes from the Early History of Astronomy*: Springer-Verlag, New York, 172pp.

Casson, Lionel (2001) *Libraries in the Ancient World*: Yale University press, New Haven, 177pp.

Evans, James (1998) *The History and Practice of Ancient Astronomy*: Oxford University Press, New York, 480pp.

Hale, William Harlan (2001) *Ancient Greece*: Horizon, American heritage, Inc., 254pp.

Hetherington, Norriss S., ed. (1993) *Cosmology: Historical, Literary, Philosophical, Religious, and Scientific Perspectives*: Garland Reference library of the Humanities, Vol. 1634, Garland Publishing Co., New York, 631pp.

Hoskin, Michael, ed. (1999) *The Cambridge Concise History of Astronomy*: Cambridge University Press, 362pp.

Lindberg, David C. (1992) *The Beginnings of Western Science*: The University of Chicago Press, 455pp.

Mlodinow, Leonard (2001) *Euclid's Window: The Story of Geometry from Parallel Lines to Hyperspace*: Touchstone; Simon and Schuster, New York, 306.

Millar, David, Ian, John, and Margaret (2002) *The Cambridge Dictionary of Scientists*: Cambridge University Press, 428pp.

Padamsee, Hasan S. (2003) *Unifying the Universe: The Physics of Heaven and Earth*: Institute of Physics Publishing, Bristol and Philadelphia, 667pp.

Sagan, Carl (1980) *Cosmos*: Random House, Inc., 365pp.

Table 3.1. **Greek Philosophers**

Thales (Miletus, c.624-546 B.C.)

Anaximander (Miletus; student of Thales, 610-545 BC)

Pythagoras (Samos; contemporary of Thales, c.570-475 B.C.)

Anaxagoras (Lampsacus [Turkey], c.500-428 B.C.)

Aristarchus (Samos, c.320-250 B.C.)

Hipparchus (Isle of Rhodes, c.170-125 B.C.)

Plato (Athens, 430-347 B.C.)

Aristotle (Athens; student of Plato, 384-322 B.C.)

Apollonius (262-190 B.C.)

Eudoxus (Cnidus, c.408-355 B.C.)

Eratosthenes (Alexandria, 276-194 B.C.)

Ptolemy (Alexandria, 90-170 A.D.)