Chapter 2: Ancient Cosmology: The Earth-Centered Universe

To ancient humans, nature must have seemed an overpowering presence. The magnificent night-time sky, with the constellations of stars, the Milky Way, the Moon, and the wandering points of light called "planets," must have filled them with a great sense of awe. It is no wonder that humans developed mythologies built around natural events. These involved Sun gods, thunder gods, and other super-human beings imagined to control the forces of nature. However, as civilization progressed, humans started to notice a number of repeatable patterns, some of which were very useful in a practical sense. For example, the month when the Nile River flooded, important to the timing of the planting of crops, corresponded to a certain position of the Sun in the sky, which moved north and south during the course of a year. The astronomers of Babylon and India were able to predict eclipses of the Sun and Moon by noticing that their timing followed a well-defined mathematical pattern. Because humans are inquisitive by nature, they eventually began to study nature methodically through a process called "science." It was in the Golden Age of ancient Greece that science was first developed systematically.

The Greek scholars inherited the knowledge of nature accumulated by the Babylonians, Egyptians, and others. They used concepts of philosophy and geometry to devise models for explaining natural phenomena. They based their thoughts on two fundamental assumptions: (1) nature is beautiful and (2) the world is logical. As discussed in Chapter 1, beauty in this sense is related to symmetry. The most symmetric three-dimensional form is a sphere, whose surface is at the same distance from its center in every direction. Similarly, the circle is the most symmetric two-dimensional figure. For this reason, Greek models of the universe assumed that celestial bodies are spheres and that their motions are circular. This notion was supported by the circular appearance of the Sun and Moon, as one would expect if their three-dimensional forms were spherical.

The use of logic to infer the nature of the universe was an extremely important advance that allowed Greek scientists to develop promising hypotheses to explain natural phenomena. The main difference between ancient and modern science is that the Greeks did not, in general, test their hypotheses through experimentation, although they did engage in passive observations to see whether actual events supported their ideas.

Greek Models of the Universe

*The Pythagoreans***:** The first main conceptual framework for thinking about the universe was introduced by the Pythagoreans, whose founder, Pythagoras of Ionia, lived until ca. 497 B.C. The Pythagoreans developed the concept that all objects in the sky are situated on "celestial spheres." This idea dominated models of the universe for more than two millennia. The Greeks imagined the spheres to be composed of transparent crystal, but they can be considered as non-physical mathematical forms as well.

Pythagoras preached that "all is number." A prime example was the numerical patterns in the study of music that he discovered. For instance, on stringed instruments (in which the tension on all strings is equal), one string plays a note that is an octave higher than another that is twice as long. (We will discuss the concept of musical pitch in more detail in Ch. 5.) The Pythagoreans and other Greek scientists speculated that the orbital motions of planets follow similar patterns, which came to be known as the "Music of the Spheres."

The Pythagoreans deduced why the Moon goes through a cycle of phases every month. Its light is merely reflected sunlight, so that only half of its surface is lit up at any given time. As the Moon orbits the Earth, we see a changing portion of the Moon's illuminated half (see Fig. 2-1). The fact that the "terminator" between the dark and light sections is curved during the crescent and gibbous phases demonstrated to them that the Moon is spherical rather than disk-shaped (see Fig. 2-2). Anaxagoras (*ca*. 500-428 B.C.) explained correctly that a solar eclipse occurs when the Moon's shadow sweeps across the Earth during the new-moon phase, while a lunar eclipse occurs when the Moon moves into the Earth's shadow during the full-moon phase.

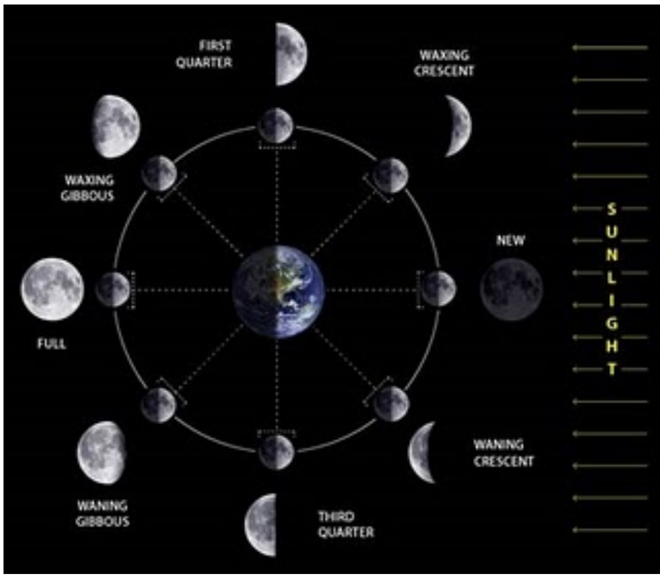


Figure 2-1. The Moon orbits the Earth, so that we see different portions of the illuminated hemisphere of the Moon. The view from the Earth is given along the bottom of the diagram, with numbers corresponding to different marked positions in the orbit. (Note: This diagram is not drawn to scale. If it were, the radius of the Moon's orbit would be 30 Earth diameters.) [Source: http://ashleymatekel.blogspot.com/2008_09_01_archive.html

Figure 2-2. The curved shape of the terminator – the line separating the dark and bright sections of the Moon – demonstrates that the Moon has a spherical shape.

The Atomists: Democritus (5th century B.C.) led a school of thought based on the concept that all matter is composed of small, indivisible pieces called "atoms." The atomists correctly speculated that the Milky Way, a cloud-like band across the sky easily seen on clear nights from a dark site, is composed of many stars that are unresolved to the naked eye. They also considered the universe to have a beginning, called the "Big Swerve," in which an initially uniform distribution of atoms at rest was disturbed, causing them to move and clump together.

Plato: The great philosopher (see Chapter 1) Plato (ca. 427-347 B.C.) developed models of the universe based on the celestial spheres of the Pythagoreans, and Eudoxus (ca. 385 B.C.) from Plato's school devised a model that used 27 concentric spheres to explain the motions of the Sun, Moon, planets, and stars. Plato, however, was very much a theorist, and rarely observed the sky to test the models proposed by him and his students. Had he done so, he would have found that models of the universe in which celestial objects move in circles around a stationary Earth cannot reproduce accurately the actual motions of the Sun, Moon, and planets.

Aristotle: The ancient philosopher-scientist most influential in western thought until the Renaissance period was Aristotle (ca. 384-322 B.C.). A student of Plato, Aristotle was a well-rounded scientist devoted as much to observation of nature as he was to developing logical theories. As was true for all the Greeks, Aristotle assumed that the universe is beautiful, which for him required that it be both symmetric and simple in form.

Aristotle's model of the universe was spherical and finite, with the Earth at the center and with the celestial bodies located on 55 different crystalline spheres, each turning at a different rate. He deduced that the Earth, too, is spherical, based on several arguments:
1. The shadow of the Earth on the Moon is curved during a lunar eclipse.
2. The elevation of the North Star (Polaris) above the northern horizon decreases as one travels south.
3. Theoretically, one would expect that material falling toward a center would take on a spherical shape.
4. Elephants are found in both Morocco and India, which therefore are not as far apart as would be required if the Earth were flat. Of course, this argument is specious, and illustrates that even great minds can concoct rather bizarre arguments to support their conclusions!

Aristotle separated the Earth and Moon from the heavens to develop a general theory of nature. Within the Earthly realm, all material is composed of four elements: earth, air, water, and fire (often jokingly referred to as Aristotle's "periodic table"). The natural tendency of earth and water is to fall toward the center of the Earth – with heavier objects falling faster than lighter ones – while air and fire rise. Besides such "natural" motions, motion could be forced, such as when a human pushes on an object. He described an object falling toward the Earth, such as a dropped stone, as moving at a constant velocity toward the center of the Earth after an initial, brief period of acceleration. Aristotle proposed that all celestial bodies beyond the Moon are composed of a fifth element, the "quintessence" or "aether," which never ages or otherwise changes. Here, all motions are "natural," *i.e.*, circular about the Earth with constant speeds.

As did the Greek scientists before him, Aristotle erroneously assumed that the Earth is stationary, but he had evidence to support this notion: If the Earth moved, for example around the Sun, then the positions of the stars would appear to shift in the sky, since we would be observing them from different locations at different times (see Fig. 2-3). This effect, called parallax, does indeed occur, but the stars are so far from the solar system that the effect is very small and can only be observed using a large telescope. The Greeks had not imagined that the stars could be so distant relative to the planets and the Sun. Hence, they felt comfortable with the prevailing model of the universe that positioned the motionless Earth at the center, with the Moon, Sun, planets, and stars all moving in circles around it.

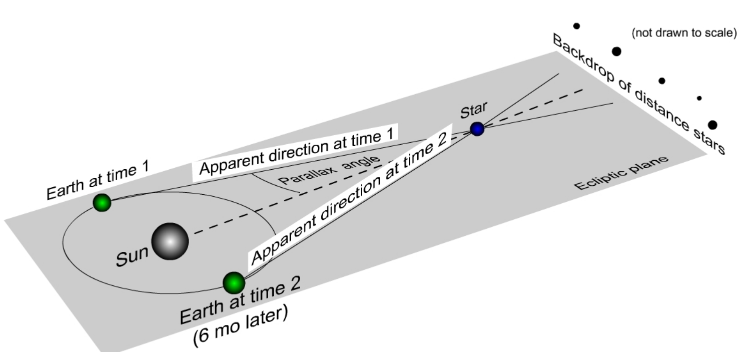


Figure 2-3. When the Earth moves as it orbits the Sun, the direction of a nearby star should shift relative to much more distant stars that form a background. The ancient Greeks did not observe this effect, and therefore erroneously rejected the idea that the Earth orbits the Sun. [Note that the drawing is not to scale; the nearest star is about 300,000 times as far away as the distance from the Sun to the Earth.]

A Sun-centered (Heliocentric) Model: One Greek scientist who did not believe that the Earth is the motionless center of the universe was Aristarchus *(ca*. 310-230 B.C.) of Samos. Only one of his works survived past ancient times, but his model of the universe was reported by others. According to Aristarchus, the Earth and other planets orbit around the Sun, which lies at the center of the universe. In this case, the daily motions of the stars, Sun, Moon, and planets must be caused by rotation (*i.e.*, spin) of the Earth, while the apparent motion of the Sun relative to the constellations of stars results from the Earth's orbit around the Sun. In this model, only the Moon still orbits around the Earth. Although, in general terms, this is the same as the modern description of the solar system, Aristarchus maintained the Greek belief in circular orbits with constant speeds, This resulted in poor agreement between his model and the observed changes of positions of the planets (as well as the Sun and Moon) with time. Furthermore, the fact that no parallaxes (see Fig. 2-3) were observed by the Greeks seemed to rule out the notion that the Earth moved.

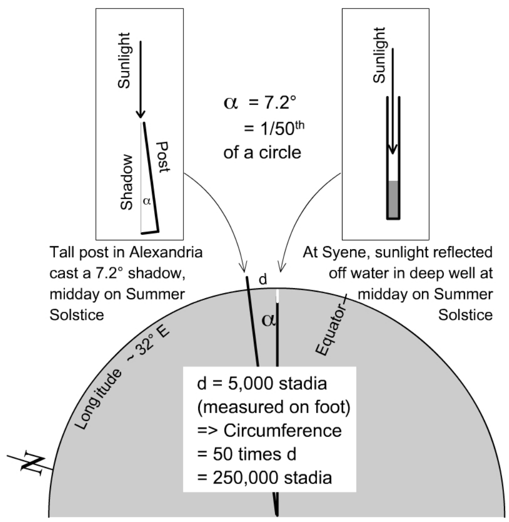


Figure 2-4. Sketch of the method that Eratosthenes used to measure the circumference and therefore the diameter of the Earth.

The Diameter of the Earth: Another important contribution was made by Eratosthenes *(ca.* 276-195 B.C.), from the Alexandrian school, who devised a method to determine the diameter of the Earth (see Fig. 2-4). He noticed that, on the summer solstice (today we define this as June 21), the Sun passed directly overhead in Syene (in Egypt), since it shone all the way down a deep well. In Alexandria, 800 km to the north, a tall post had a shadow at noon equal to 1/8 of its height. He then reasoned that, since the Sun was very far away (as was determined by Aristarchus) compared to 800 km (actually, 5000 stadia, then the main unit of measurement for long distances), its rays can be considered essentially parallel. In this case, the tangent of the angle between the line from the center of the Earth to Syene and the line from the center to Alexandria must be 1/8. The angle is then 7.2° =1/50 of a circle (360°). The circumference of the Earth must therefore be 50×800 km = 40,000 km and the diameter is this divided by π, or 13,000 km. This value is correct to within two significant digits.

Astronomical Measurements: The astronomer Hipparchus *(ca.* 180-125 B.C.) provided the finishing touch to the scientific accomplishments of the ancient world through his careful observations and calculations. His accomplishments included:

1. the most accurate star map of that era, complete with celestial coordinates
2. his discovery that the Earth's axis of rotation precesses (*i.e.*, the direction in which it points traces out a circle in the sky) with a period of 26,000 years
3. the classification of brightnesses of stars in six "magnitude" categories
4. the determination of the length of the year to within six-minute accuracy, complete with an estimate of the maximum measurement error (15 minutes)

5. the computation of the distance to the Moon as 59 times the radius of the Earth (the actual value is 60) from the size of the Earth's shadow relative to the Moon's diameter and the duration of a lunar eclipse
6. a method for predicting the position of the Sun in the sky on any date with an accuracy that was better than could be measured by observation; he did the same for the Moon, although with lower accuracy.

Hipparchus also produced his own version of the crystalline-sphere model of the universe. By this stage, in order to try to reproduce the measurements of positions of the Sun, Moon, and planets as a function of time, the models had become quite complex. Instead of simple motion in a circle centered on the Earth, each planet was imagined to have a circular orbit about a point in space that itself orbited in a circle that was not exactly centered on the Earth. The "simplicity" of the universe insisted upon by Aristotle had been abandoned because simple models did not agree with the observational facts.

Accomplishments of Ancient Greek Science: By the end of the Golden Age, the Greeks had invented science by devising models for natural phenomena and using these models to make predictions that could test the models. They did this by developing science alongside philosophy, geometry, and mathematics, which they used extensively when formulating their hypotheses. They understood the cause of the lunar cycle, determined that the Earth, Moon, and Sun were spherical, and measured their relative distances and sizes, in many cases quite accurately. Their basic model of the universe revolving around a stationary Earth was incorrect. But they had a good reason for rejecting the alternative model that everything revolves about the Sun: the Sun-centered model predicts that the position of stars on the sky should shift back and forth, but they were unable to measure such a shift. The insistence of the Greek scientists that models of nature must reproduce the observations remains to this day the basic tenet of science.

Box 2-1. Fundamental observations of the naked-eye cosmos

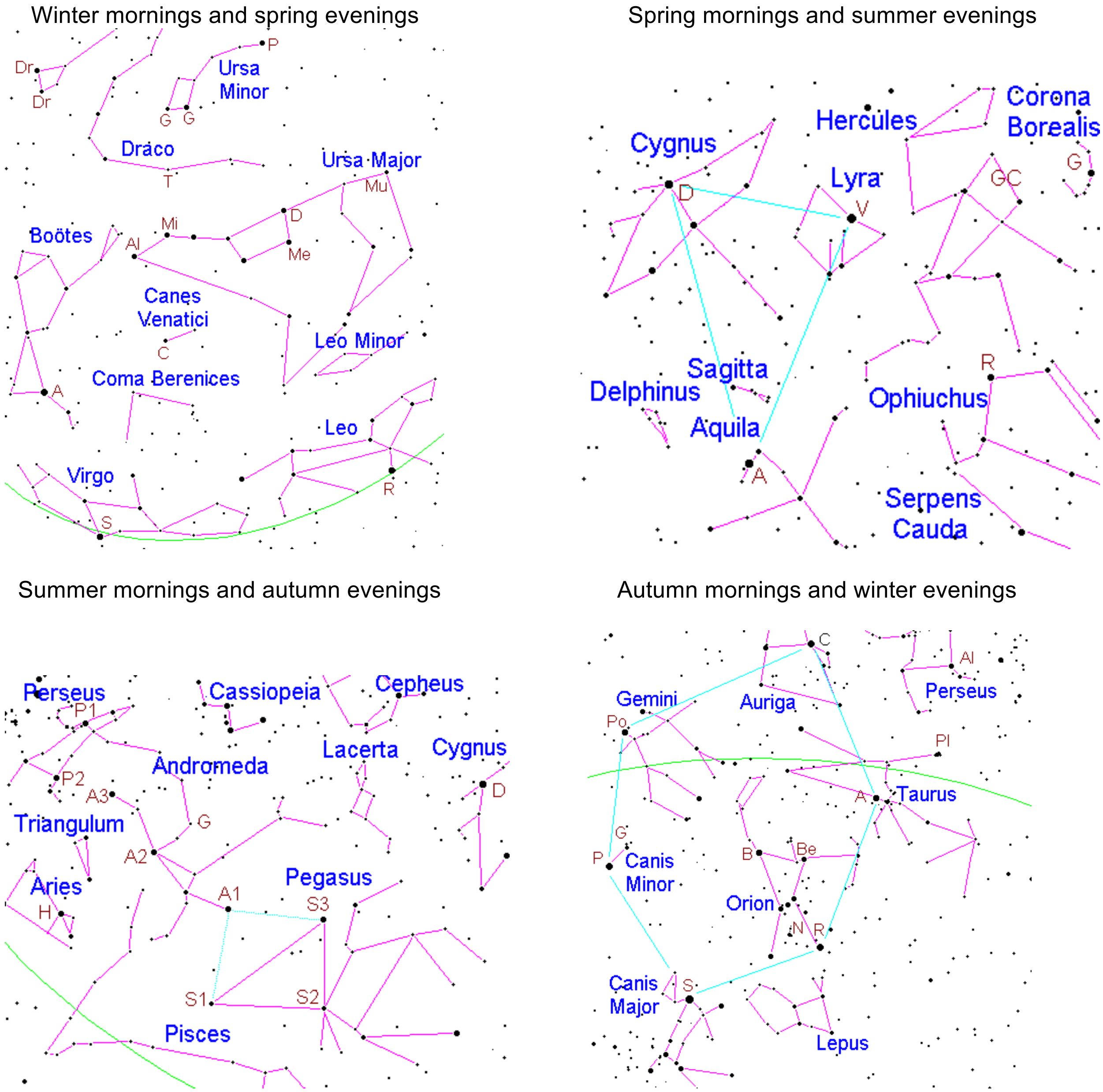
The ancient models of the universe were based on how the sky appears to the human eye:

Apparent motion of the stars: In the night sky, we can see several thousand stars, the relative positions of which remain nearly fixed over human lifetimes. (Changes are noticeable to the naked eye only after thousands of years.) The stars are grouped into patterns called "constellations," but the boundaries between constellations are arbitrary and of no significance except as convenient reference points.

Figure 2-5. Time lapsed photographs of the stars near the north (*left*) and south (*right*) celestial poles, showing how the stars appear to move in circles about the poles as the Earth rotates. [From (*left*) www.skyandtelescope.com and (*right*) www.astrographics.com]

The sky appears to rotate east to west during the night about a point near the North Star, Polaris (or, in the southern hemisphere, about a point that contains no bright stars; see Fig. 2-5). One rotation occurs in 23 hours, 56 minutes, so that after one year, 366 such rotations have occurred (367 in a leap year). Because this time of rotation differs from clock time by about 4 minutes per day, the stars that are visible at any given time of night, say 9:00, change with the seasons. Exceptions are stars near the celestial poles (see Fig. 2-5). For observers in the northern hemisphere, this means stars near Polaris.

Figure 2-6. Constellations Visible Overhead from Northern Latitudes during Different Seasons (from www.umich.edu/~lowbrows/guide)



Apparent motion of the Sun: The Sun also rises in the east and sets in the west. The time it takes between successive crossings of the meridian – an imaginary north-south arc on the sky – is 24 hours. The Sun's position gradually moves eastward from day to day along the 12 constellations of the ecliptic (the "zodiac"), such that it completes a cycle in 365.24 days = 1 year. The Sun reaches its highest elevation above the southern horizon (northern horizon for observers in the southern hemisphere) when it passes the meridian at about noon. The exact time depends on where you are located within your time zone. When it is summer in the northern (winter in the southern) hemisphere, the Sun rises in the northeast, reaches a high (low in the southern hemisphere) elevation at noon, and sets in the northwest. At the spring and autumnal equinoxes, the Sun rises due east, reaches an elevation at noon equal to 90° minus the observer's latitude, and sets due west. During winter in the northern hemisphere (summer in the southern hemisphere), the Sun rises in the southeast, reaches a low elevation (high in the southern hemisphere) at noon, and sets in the southwest.

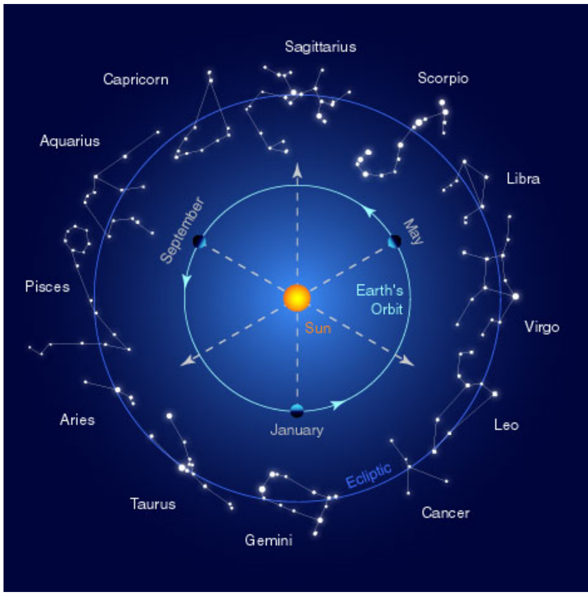
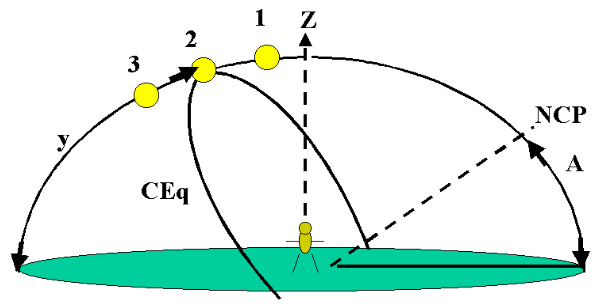


Figure 2.7. *Left:* Cycle of sky motions of the Sun because of the Earth's orbit. Our line of sight, shown by the arrows at 3 different months, determines the constellation where the Sun appears. [From www.lcsd.gov.hk/CE/Museum/Space/ EducationResource/Universe] *Below:* The noon-time elevation of the Sun at (1) June 21, (2) March 19 & September 22, and (3) December 21. [From www.courses.psu.edu/astro/astro001_pjm25]



The Moon also rises in the east and sets in the west, but appears to move eastward relative to the stars by one apparent lunar diameter every 55 minutes. The Moon therefore reappears in the same constellation every 27.3 days. Because the Sun's position has moved during that time, it takes 29.5 days for the Moon to return to the same phase (*e.g.*, full). The phase is determined by the relative positions of Earth, Moon, and Sun. During each 29.5-day period, the Moon goes through all phases (Fig. 2-1.) As occurs for the Sun and all planets, the Moon's motion is along the constellations of the ecliptic.

Angular Measurements on the Sky: When we speak of sizes or distances on the sky, we do so in angular units. This is because we cannot measure the distances to celestial objects easily, just as the physical size of an airplane cannot be determined solely by measuring how big it appears in the sky. Hence, the Moon's "size," 0.5° or 30′ (30 arcminutes), is measured by the angle subtended by lines between the western edge of the Moon, the eye and the eastern edge of the Moon; see Figure 2-8. The Sun has about the same angular size as the Moon.

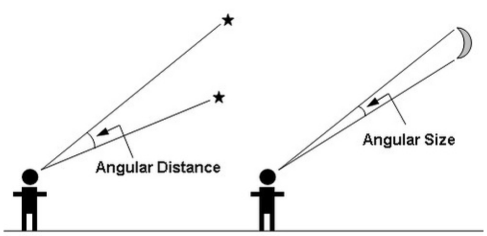


Figure 2-8. Separations of objects on the sky and sizes of celestial objects are measured in angular units. [From mydarksky.org/2008/04/16/common-stargazing-terms-2]

Apparent motions of the planets: Because the planets are all orbiting the Sun and our observing platform – the Earth – is doing so as well, the motions of the planets on the sky are rather complex. All rise in the east and set in the west. Mercury and Venus are never very far from the Sun on the sky, and rise or set within about an hour and 2.5 hours of the Sun, respectively. As they emerge from being next to the Sun – to be seen before sunrise – they become brighter and move more slowly relative to the stars from day to day as they move east to west ("retrograde," or reverse motion) through the constellations. After a few weeks (Mercury) or months (Venus,) this motion reverses and the planet moves eastward ("prograde") among the stars, fading in brightness until it again passes near the Sun and appears in the evening sky. Now it becomes brighter with time, eventually stopping its prograde motion and reverting to retrograde motion, speeding up and fading once more as it again approaches the position of the Sun.

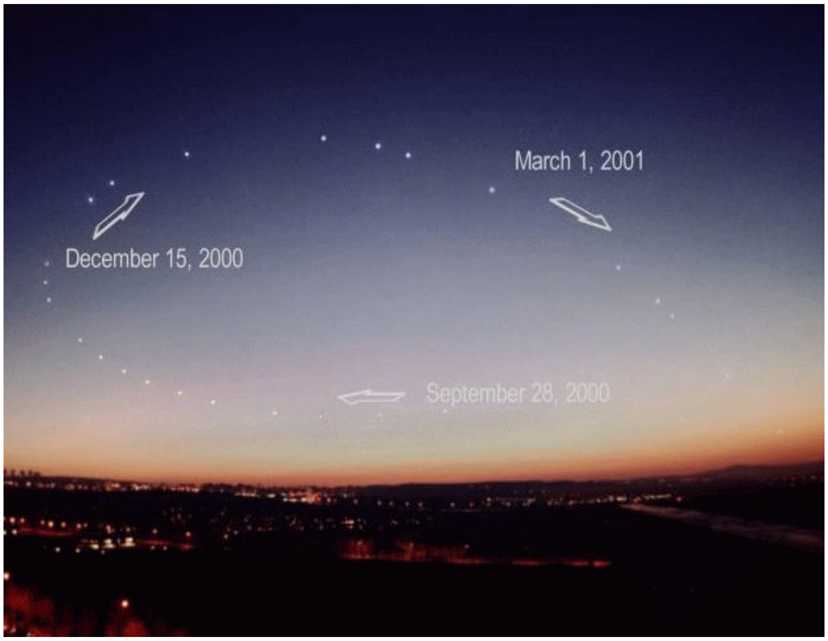


Figure 2-9. *Left:* Superposed photographs of Venus looking toward the western horizon shortly after Sunset on different dates in 2000-01. Note that the elevation above the horizon – and therefore apparent separation from the Sun – changes with time. The north-south (right-left on the image) motion is caused by the changing position of the Sun through the seasons. *Below:* The apparent motion of the planets other than Mercury and Venus follows a loop at the time when the planet rises near Sunset. The eastward motion is called "prograde" while the westward motion is "retrograde." [Both figures from astro.unl.edu/ naap/ssm/elongation.html]

The remaining planets (only Mars, Jupiter, Saturn, and – barely – Uranus can be seen with the naked eye) move more slowly relative to the stars. Unlike Mercury and Venus, they can be either close to the Sun in the sky, on the opposite side of the sky, or in between. The motion is usually prograde (eastward) relative to the stars, but when the planet rises near sunset (*i.e.*, when it is on the opposite side of the sky from the Sun, called "opposition") its motion is retrograde. This causes the position of the planet relative to the constellations to execute a tight loop (see Fig. 2-9). The planet (especially Mars) is also somewhat brighter when near opposition than at other times. This retrograde motion of outer planets was difficult for geocentric (Earth-centered) models to explain. The motion of Mars is quite non-uniform: it speeds up and slows down in a fairly complex way.

Occasional Celestial Events: Other predictable events include solar and lunar eclipses, each of which (partial or total eclipse) can usually be viewed from somewhere on Earth 2-5 times per year. There are also annual "showers" of meteors that orbit the Sun in swarms. In addition, there are random occurrences such as the appearances of non-shower meteors (typically tens per night), comets (several per decade), and previously invisible stars that brighten suddenly and then fade gradually (roughly 1 per century).

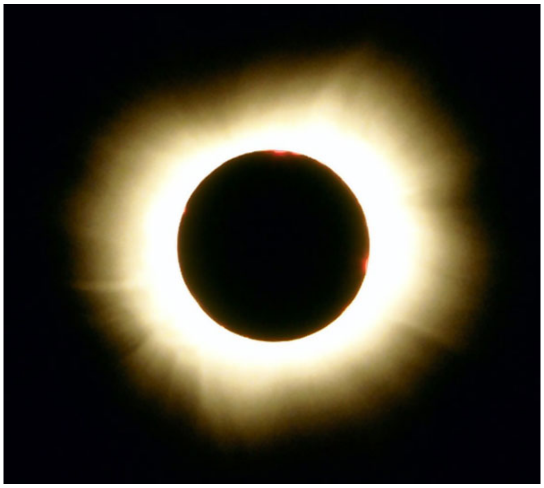



Figure 2-10. Occasional celestial events. *Left:* Solar eclipse, when the Moon passes in front of the Sun so that we only see the outer, thin layer of the Sun, the corona. [From www.whirlpoolgalaxy.com] *Right:* Comet Hale-Bopp, which could be seen easily with the unaided eye in 1997. [From wikipedia.com]

After the Golden Age: Ptolemy to the Scholastics

Claudius Ptolemaeus, or simply Ptolemy (*ca.* 100-165 A.D.), was an astronomer in Alexandria who developed an extremely detailed model of the universe that was used for nearly 15 centuries to predict the positions of celestial objects. The model was of the same nature as, but even more complex than, that devised by Hipparchus. This did not bother Ptolemy, who recognized the model as a tool for calculation rather than a representation of reality. Despite this, scientists today often mock Ptolemy's model as the prime example of a ridiculously complex scientific theory. The main (now known to be incorrect) conceptual change made by Ptolemy was to allow the planets to move faster in their orbits around the Earth when they are on the opposite side of the Earth from the Sun. With that modification, Ptolemy's model was able to predict fairly accurately the positions of the planets as a function of time, the dates and times of eclipses, and other astronomical events. For this reason, his main writing was referred to as the *Almagest*, which is a Greek adaptation of an Arabic word meaning "the Greatest."

By the sixth century A.D., science in Europe had fallen into disarray. In the Arabic world, however, it thrived. Baghdad was the site of a major scientific center, where detailed astronomical observations were made and recorded. In fact, the common names of many bright stars are Arabic in origin. Nevertheless, no major competitor to Ptolemy's model appeared until the Renaissance.

Greek thought was revived in the 13th century by Thomas Aquinas, who led the scholastic movement. Although his activities were at first opposed by the Roman Catholic Church, he eventually convinced the Church leaders that the classic Greek ideas were compatible with Christian teachings. Before long, Greek notions, such as the idea that the universe revolves around the stationary Earth, had become part of the Church's orthodoxy. Those who contradicted this viewpoint were branded as heretics. In the next chapter, we discuss this conflict between scientific inquiry and "revealed truth," which became acute during the Renaissance.

Summary

Modern science owes its origin to the ancient Greeks, who developed geometrical models of the universe in an attempt to explain natural phenomena. Their models were based on the assumption that the universe is symmetrical and logical. Their attempts to describe nature therefore used spherical bodies and circular orbits – usually with constant orbital velocities – placed on spherical shells in the celestial sphere that represented the entire universe. These were geocentric (Earth-centered) systems. A heliocentric (sun-centered) model, with the Earth spinning once per day about its polar axis, was rejected on the grounds that it predicted parallaxes – back-and-forth shifts in position on the sky – of stars as the Earth changed positions in its orbit around the Sun. They did not observe any parallaxes. The ancient Greeks did not realize that the stars are so distant that this effect cannot be seen by the unaided eye.

The Greeks were able to determine:
• the causes of the phases of the Moon and eclipses
• the spherical shapes of the Earth, Moon, and (by analogy and its circular appearance) Sun
• the diameter of the Earth
• the distance of the Moon from the Earth (and, from this, the diameter of the Moon)
• the 26,000-year period of precession (tracing of a circle) of the direction of the Earth's polar axis

The ancient Greek geocentric models of the universe became more complex as they tried to predict more accurately the times of celestial events and the positions of the planets, Sun, and Moon on the sky. This process culminated in the work of Ptolemy of Alexandria (2nd century A.D.), whose complex model was used for more than a millennium.

Note to the Student: You should become familiar with the observations of the sky that can be made with the naked eye, as summarized in the boxed section "Fundamental Observations of the Naked-Eye Cosmos."

Glossary

Celestial sphere: Erroneous but sometimes useful concept used to describe the apparent placement of heavenly bodies in the sky. It seems as if they are on the inside of spherical shells with the Earth at the center.

Geocentric model: The Earth is stationary and at the center of the universe. The Sun and (in most versions) the planets and stars revolve around the Earth.

Heliocentric model: The Sun is the stationary center of the solar system. All planets orbit around the Sun.

Parallax: The back-and-forth shift expected in the apparent position of a star if the Earth orbits the Sun. The effect is caused by changing the observer's perspective, which changes the direction of the line of sight to a celestial object. See Figure 2-3.

Zenith: The direction that is straight up, 90º above the horizon.

Meridian: An imaginary semi-circle in the sky that starts at the northern horizon, passes through the zenith, and ends at the southern horizon at the observer's location.

Constellation: One of 88 areas used to divide the sky into a reasonable number of regions. The stars in a constellation just happen to be located in the same direction; most of them are not physically associated.

Angular size: Apparent size of an object in the sky. It is the angle subtended by two lines of sight, one pointing from the observer's eye to one side of the object and the other pointing from the same eye to the other side of the object. See Figure 2-8.

Angular distance: Apparent separation of two objects in the sky. It is the angle that would be subtended by two lines of sight, one pointing from your eye to one object and the other pointing from the same eye to the other object. See Figure 2-8.

Opposition: When a planet is on the opposite side of the Earth than the Sun is (not possible for the inner planets Venus and Mercury). The planet then rises at about the time of sunset.

Prograde motion: The night-to-night west-to-east motion *relative to the background stars* executed by the Sun, planets, and Moon because of their orbital motions.

Retrograde motion: The apparent "backward" (east to west *relative to the background stars*) night-to-night motion of a planet. Caused by the Earth passing a slower, outer planet or an inner planet passing the Earth as the two orbit the Sun at different speeds.

Questions for Discussion

A. What were advantages of the philosophical/geometrical assumptions (*e.g.*, circular orbits) made by the ancient Greek scientists when they developed their models of the universe? What were the disadvantages?

B. Was the rejection of the heliocentric model by the ancient Greeks, based on their inability to detect parallaxes of stars, a strong or weak point of their methodology? What lessons can we learn from this error, which misled scientists for nearly two millennia?

C. What was gained by Ptolemy's complex model of the solar system? What were its main drawbacks?

Homework Assignment

Instructions: Below are stated the two hypotheses that could explain why the Earth has seasons (winter, spring, summer, and autumn). For **each** of these hypotheses, give **two** possible **observational tests** that can be performed from the surface of the Earth that would serve to support or refute the hypothesis. Be as specific as possible about the prediction made and what would be observed. (An example of a specific, although incorrect, prediction might be: "If you were in Boston and faced north, you would see the Sun rise directly in front of you at 6:00 every morning throughout the year.")

Please note that the construction of a scale model, while often useful, is not an observational test! Also note that you are **not** testing whether summer is hot and winter is cold; assume that you know when it is summer and when it is winter.

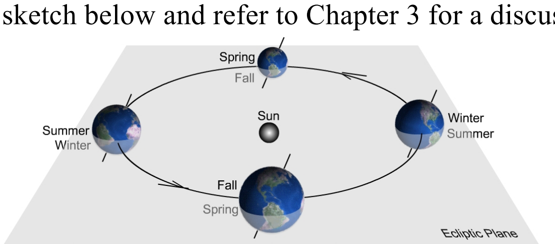
If you know what the outcome would be of the observational test, state this outcome and whether it would support or refute the hypothesis. This is not necessary, however.
Your answer should contain **4 observational tests**, two for each of the two hypotheses. However, a similar test can be proposed for both hypotheses if the outcome of the test is predicted to be different.

Observed: In Boston, there are 4 seasons: winter (cold), summer (hot), fall, and spring (intermediate). Note that this is given, so that measuring temperatures is therefore not a legitimate test!

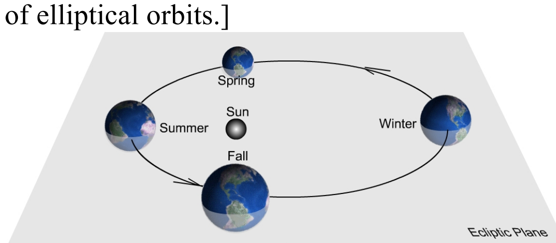
Hypothesis 1: *The Earth revolves around the Sun in a nearly circular orbit in the ecliptic plane, so its distance from the Sun is nearly constant. However, the Earth's spin axis (it spins once per day) is tilted with respect to the orbit and always points in the same direction (toward the star Polaris). This causes sunlight to shine more directly on the surface of the spherical Earth in summer and less directly in winter. The more intense sunlight in summer is the reason for the warmer temperatures during that season.*

Advice: see the sketch below. Note that the distance from the Earth to the sun is actually much greater than the Earth's diameter, so the distance of the northern hemisphere from the Sun is negligibly different from the distance of the southern hemisphere from the Sun at all times. The directness of the sunlight – whether it shines obliquely on the surface or almost straight down – is similar to the light shone on the wall by a flashlight: more intense when pointed straight toward the wall and less when at an angle.

Hypothesis 2: *The Earth revolves around the Sun in an elongated elliptical orbit. This causes the Earth to be significantly closer to the Sun at some times than at others. Summer (hot season) occurs when the Earth is close to the Sun and winter (cold season) occurs when it is farther from the Sun in this elliptical orbit.* [*Note*: In an elliptical orbit around the Sun, the Sun lies at one focus of the ellipse, not at the center, so that there is only one point in the orbit closest to the Sun and one point farthest from the Sun. See the sketch below and refer to Chapter 3 for a discussion of elliptical orbits.]



Hypothesis 1 for the Earth's seasons. The spin axis of the Earth always points in the same direction and the Earth's distance from the Sun is nearly constant. When the northern axis (up in the diagram) points more toward the Sun, the northern hemisphere experiences summer, and when it points away, it experiences winter.



Hypothesis 2 for the Earth's seasons. The Earth's orbit is in the shape of an elongated ellipse. When the Earth is closest to the Sun, we experience summer, and when it farthest from the Sun, we experience winter.

Note: neither diagram is drawn to scale.