Part 1 Changing views and fundamental concepts

1 Evolving perspectives: a historical prologue

- The wandering planets move in a narrow track against the unchanging background stars, and some of these vagabonds can suddenly turn around, apparently moving in the opposite direction before continuing on their usual course.
- The ancient Greeks noticed that the Earth always casts a curved shadow on the Moon during a lunar eclipse, demonstrating that our planet is a sphere.
- For centuries, astronomers tried to describe the observed planetary motions using uniform, circular motions with the stationary Earth at the center and with the distant celestial sphere revolving about the Earth once a day.
- Around 145 AD, Claudius Ptolemy devised an intricate system of uniform motion around small and large circles to model the motions of the Sun, Moon and planets around a stationary Earth; his model was used to predict their location in the sky for more than a thousand years.
- The stars seem to be revolving around the Earth each night, but the Earth is instead spinning beneath the stars. This rotation also causes the Sun to move across the sky each day.
- Mikolaj Kopernik, better known as Nicolaus Copernicus, argued in 1543 that the Earth is just one of several planets that are whirling endlessly about the Sun, all moving in the same direction but at different distances from the Sun and with speeds that decrease with increasing distance.
- Almost four centuries ago, Johannes Kepler used accurate observations, obtained by Tycho Brahe, to conclude that the planets move in ellipses, or ovals, with the Sun at one focus, and to infer a precise mathematical relation between the mean orbital distance and period of each planet.
- More distant planets take longer to move once around the Sun and they move with slower speeds; their orbital periods are in proportion to the cubes of their distances.
- Astronomy is an instrument-driven science in which novel telescopes and new technology enable us to discover cosmic objects that are otherwise invisible and hitherto unknown.

- Many major astronomical discoveries have been unanticipated and serendipitous, made while new telescopes were used to study other, known cosmic objects; the earliest of these accidental discoveries include the four large moons of Jupiter, the planet Uranus, and the first known asteroid, Ceres, discovered respectively by Galileo Galilei in 1610, William Herschel in 1781, and Giuseppe Piazzi in 1801.
- The asteroid belt between the orbits of Mars and Jupiter contains more than 500 000 asteroids, but it is largely empty space and has a total mass that is much less than that of the Earth's Moon.
- Two kinds of telescopes, the refractor and the reflector, enable astronomers to detect faint objects that cannot be seen with the unaided eye, and to resolve fine details on luminous planets that otherwise remain blurred.
- Jupiter, Saturn and Uranus have a retinue of large satellites, and Neptune has only one really large moon that moves in the opposite direction to all the other large satellites. Mercury and Venus have no moons, the Earth has one satellite, our Moon, and Mars has two very small ones.
- Christiaan Huygens discovered Saturn's rings in 1659; they are completely detached from the planet and consist of innumerable tiny satellites each with an independent orbit about Saturn.
- In his *Principia*, published in 1686, Isaac Newton showed how the laws of motion and universal gravitation describe the movements of the planets and everything else in the Universe.
- The solar system is held together by the Sun's gravitational attraction, which keeps the planets in their orbits; they move at precisely the right speed required to just overcome the pull of solar gravity.
- The gravitational attraction between two objects increases in proportion to the product of their masses and in inverse proportion to the square of the distance between them.
- The planet Neptune was discovered in 1846, near the location predicted by mathematical calculations under the assumption that the gravitational pull of a large, unknown world, located far beyond Uranus, was causing the observed positions of Uranus to deviate from its predicted ones.
- Estimates for the mean Earth–Sun distance, known as the astronomical unit or AU, were gradually refined over the centuries, eventually setting the scale of the solar system at 1 AU = 149.6 million kilometers. At this distance, it takes 499 seconds for light to travel from the Sun to the Earth.
- The nearest star other than the Sun is located at a distance of 4.24 light-years; it is about 270 000 times further away from the Earth than the Sun.
- The Sun is the most massive and largest object in our solar system. The Sun's mass, which is 333 000 times the Earth's mass, can be inferred from Kepler's third law using the Earth's orbital period of one year and the Earth's mean distance from the Sun, the AU.
- The Sun's size, at 109 times the diameter of the Earth, can be inferred from the Sun's distance and angular extent.
- The temperature of the Sun's visible disk is 5780 kelvin; it can be determined from the Sun's total irradiance of the Earth, the Earth–Sun distance or the AU, and the radius of the Sun.

- The temperature at the center of the Sun is 15.6 million kelvin, estimated from the speed a proton must be moving to counteract the gravitational compression of the massive Sun.
- The composition of the Sun is encoded in absorption lines that appear in the visible spectrum of sunlight.
- The lightest element, hydrogen, is the most abundant element in the Sun, and the next most abundant solar element, helium, was first discovered in the Sun.
- The regular spacing of hydrogen's spectral lines can be explained by quantum theory, in which the angular momentum and energy of an orbiting electron are quantized, depending on an integer quantum number.
- The eight major planets can be divided into two groups: the four rocky, dense, terrestrial planets, Mercury, Venus, Earth and Mars, located relatively near the Sun, and the four giant, low-density planets, Jupiter, Saturn, Uranus and Neptune, that are further from the Sun.
- The temperature and density increase systematically with depth in the giant planets, owing to the greater compression by overlying material.
- As the result of differentiation in their originally molten interiors, the rocky terrestrial planets contain dense iron cores surrounded by less-dense silicate mantles.
- The terrestrial planets contain partially molten, liquid cores, but their internal temperatures cool as time goes on due to the depletion of radioactive elements and the emission of internal heat.

1.1 Moving points of light

The ancient wanderers

Our remote ancestors spent their nights under dark skies, becoming intimately familiar with the stars. They looked up on any moonless night, and watched thousands of stars embedded in the black dome of the night, ceaselessly moving from one edge of the Earth to overhead and back down to another edge, night after night without end.

The brightest stars received names, and patterns, now called constellations, were noticed among groups of them. These permanent stellar beacons are always there, firmly rooted in the dark night sky, and the constellations remain unchanged over the eons.

As ancient astronomers watched the stars, they focused attention on seven objects that did not move with the stars. These celestial vagabonds changed position on the sphere of background stars from hour to hour or night to night, and unlike the stars, they would appear in the night sky at different times from year to year. Ranked in order of greatest apparent brightness, they are the Sun, Moon, Venus, Jupiter, Saturn, Mercury and Mars, each with the Latinized name of a Greek god or goddess. Our ancestors called them *planetes*, the ancient Greek word for "wanderers"; and the designation planet is still used for all but the Sun and Moon.

The Sun and Moon move with a rhythm, pattern and beat, marking out the time of our first clocks. The rising and setting Sun ticked off the days, the Moon's changing phase set the monthly cycle, and the seasons marked off the years.

The Sun does not rise at precisely the same point on the horizon each day. Instead, the location of sunrise drifts back and forth along the horizon in an annual cycle. Ancient astronomers used monuments to line up the limits of these excursions (Fig. 1.1). The length and height of the Sun's arc across the sky also change with a yearly rhythm. In the northern hemisphere, the Sun rises highest in the sky on the summer solstice, around June 21 each year, with its longest trajectory and the most daylight hours (Fig. 1.2).

Like the Sun, the Moon rises and sets at different points along the horizon, and reaches varying heights in the sky. Since the full Moon always lies nearly opposite to the Sun, the winter full Moon rises much higher in the sky than the summer full Moon.

Cambridge University Press
978-0-521-19857-8 - The Cambridge Guide to the Solar System, Second Edition
Kenneth R. Lang
Excerpt
More information

Fig. 1.1 Stonehenge The ancient stone pillars of Stonehenge in southern England, shown in this photograph, frame the rising Sun. This monument was used to find midsummer and midwinter 4000 years ago – before the invention of writing and the calendar. The Sun rises at different points on the horizon during the year, reaching its most northerly rising on Midsummer Day (summer solstice on 21 June). After this, the rising point of the Sun moves south along the horizon until it reaches its most southerly rising on Midwinter Day (winter solstice on 22 December). An observer located at the center of the main circle of stones at Stonehenge watched midsummer sunrise over a marker stone located outside the circle; other stones within the circle framed midwinter sunrise and sunset. (Courtesy of Owen Gingerich.)

The Moon repeats its motion around the Earth on a monthly cycle, periodically changing its appearance (Fig. 1.3). Once each month, the Moon comes nearly in line with the Sun, vanishing into the bright daylight. On the next night the Moon has moved away from this position, and a thin lunar crescent is seen. The crescent thickens on successive nights, reaching the rotund magnificence of full Moon in two weeks. Then, in another two weeks, the Moon disappears into the glaring Sun, completing the cycle of the month and providing another natural measure of time.

Even the earliest sky-watchers must have noticed that the wanderers are confined to a narrow track around the sky. Babylonian astronomers noticed it thousands of years ago, identifying constellations that lay along its path. Twelve of these constellations subsequently became known as the zodiac, from the Greek word for "animal". The Sun's annual path, called the ecliptic, runs along the middle of this celestial highway, and the paths of all the other wanderers lie within it. Its narrowness is a sign that the planets move almost like marbles on a table because the planes of their orbits are closely aligned with each other.

It was obvious to astronomers from the earliest times that the wanderers do not move at uniform speeds or follow simple paths across the sky. Mars apparently moved in a backwards loop for weeks at a time, seemingly disrupting its uniform progress across the night sky. It gradually came to a stop in its eastward motion, moved backward toward the west, and then turned around again and resumed moving toward the east (Fig. 1.4). Jupiter and Saturn also displayed such a temporary backwards motion in the westward retrograde direction before continuing on in the eastward prograde direction.

But why did these planets behave in such an unusual and singular manner? The ancient Greeks first proposed logical explanations, based on geometry and uniform motion, but modern explanations differ in both the locations and motions of the planets.

Circles and spheres

The ancient Greeks used geometrical models to visualize the cosmos, incorporating the symmetric forms of the circle and sphere. Their aim was to describe the regularities that underlay the planetary motions against the unchanging stellar background, and to thereby predict the locations of the planets at later times. They wanted to provide a reliable guide to the future, which is still one of the main points of science.

In arguments used by the Pythagoreans, and subsequently recorded by Aristotle (384–322 BC), it was shown that the Earth is a sphere. During a lunar eclipse, when the Moon's motion carries it through the Earth's shadow, observers at different locations invariably saw a curved shadow on the Moon (Fig. 1.5). Only a spherical body can cast a round shadow in all orientations. The curved surface of the ocean was also inferred by watching a ship disappear over the horizon; first the hull and then the mast disappear from view.

According to Plato, writing around 380 BC, the simplest and purest sort of motion was circular, so circles ought to describe the visible paths of the moving planets.

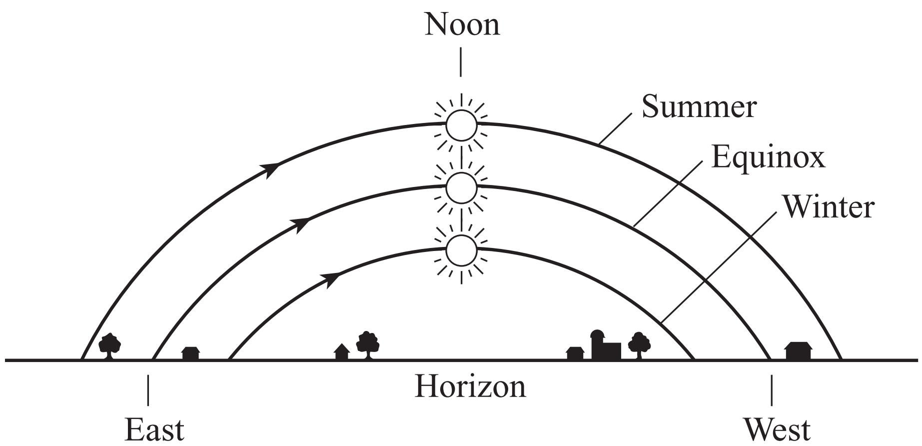

Fig. 1.2 The Sun's trajectory The Sun's motion across the sky as seen from the northern hemisphere. The maximum height of the Sun in the sky, and the Sun's rising and setting points on the horizon, change with the seasons. In the summer, the Sun rises in the northeast, reaches its highest maximum height, and stays up longest. The Sun rises southeast and remains low in the winter when the days are shortest. The length of day and night are equal on the Vernal, or Spring, Equinox (March 20) and on the Autumnal Equinox (September 23) when the Sun rises exactly east and sets exactly west.

After all, a wheel moves so well because it is round, without rough, sharp edges to get in the way. The circle also has no beginning or end, seemingly appropriate for describing the endless motion of the heavenly wanderers. And the central Earth would be separated from the heavens, like a magician who draws a boundary circle around him to seal off the region in which magical powers are brought into play.

Following Plato's suggestion, astronomers spent centuries trying to discover those uniform, perfectly regular, circular motions that would "save the appearances" presented by the planets. They supposed that the Earth stood still, an immobile globe at the center of it all. The imaginary celestial sphere of fixed stars wheeled around the central, stationary Earth once every day, with uniform circular motion and perfect regularity, night after night and year after year. Such a celestial sphere would also explain why people located at different places on Earth invariably saw just half of all the stellar heavens, and why travelers to new and distant lands would see new stars as well as new people.

The Sun, Moon and planets were once supposed to be carried on concentric, transparent crystalline spheres, which revolved around the stationary Earth, but their hypothetical uniform and circular motions contradicted observations. The Earth-centered model did not explain, for example, why each planet moved with changing speed across the sky, not at an unchanging, uniform rate.

So the Egyptian astronomer Claudius Ptolemy (fl. 150 AD) shifted the Earth from the exact center of the Universe by just a small amount, and described the planetary appearances with an intricate system of circles moving on other circles, like the gears of some fantastic cosmic machine. A planet in uniform circular motion about a center offset from the Earth would appear to a terrestrial observer to be moving with varying speed, faster when it is closest to Earth and slower when further away. Combinations of uniform circular motion were additionally required to account for the looping, or retrograde, paths of the planets (Fig. 1.6). Each planet was supposed to move with constant speed on a small circle, or epicycle, while the center of the epicycle rotated uniformly on a large circle, or deferent. In this way Ptolemy, in his *Mathematical Compilations*, or *Almagest*, written about 145 AD, was able to predict the motions of every one of the seven wanderers, compounding them from circles upon circles. By selecting suitable radii and speeds of motion, Ptolemy reproduced the apparent motions of the planets with remarkable accuracy. He succeeded so well that his model was still being used to predict the locations of the planets in the sky more than a thousand years after his death.

The Earth moves

The ancient Indians of Asia had a different point of view, supposing that the Earth moves around the Sun, as did the Greek mathematician and astronomer Aristarchos, born on the island of Samos in 310 BC. Aristarchos moved the center of the Universe from the Earth to the Sun, and set the Earth in motion, supposing that the Earth and other planets travel in circular orbits around the stationary Sun. He further stated that the fixed stars do not move, and that their apparent daily motion is due to the Earth's rotation on its axis.

Waxing
Crescent

First
Quarter

Waxing
Gibbous

Full
Moon

Cambridge University Press
978-0-521-19857-8 - The Cambridge Guide to the Solar System, Second Edition
Kenneth R. Lang
Excerpt
More information

Waning
Gibbous

Third
Quarter

Waning
Crescent

Fig. 1.3 The Moon's varying appearance During the monthly cycle, the illuminated part of the Earth's Moon waxes (grows) from crescent to gibbous, and then after full Moon, it wanes (decreases) to a crescent again. The term crescent is applied to the Moon's shape when it appears less than half-lit; it is called gibbous when it is more than half-lit but not yet fully illuminated. The reason for the Moon's changing shape is described in Fig. 1.8. (Lick Observatory Photographs.)

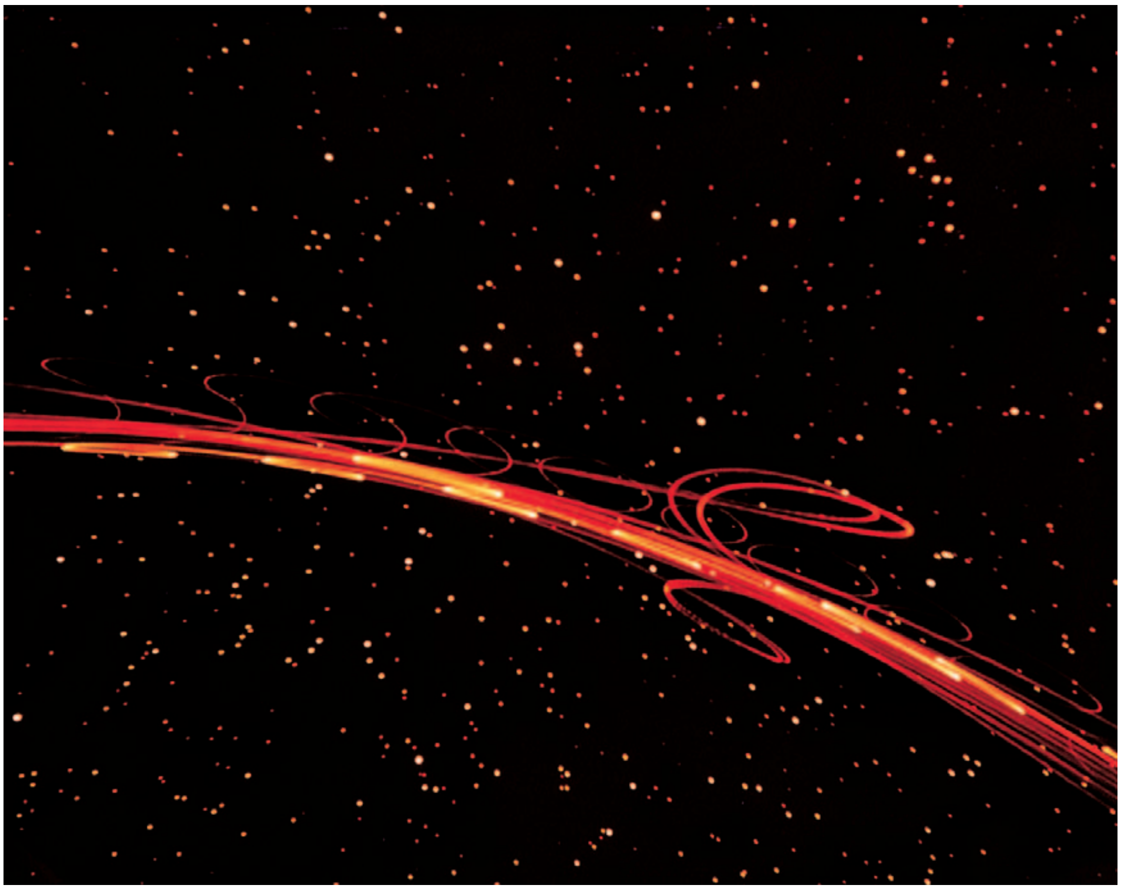

Fig. 1.4 Retrograde loops This photograph shows the apparent movements of the planets against the background stars. Mars, Jupiter and Saturn appear to stop in their orbits, then reverse direction before continuing on – a phenomenon called retrograde motion by modern astronomers. Ancient and modern explanations for this temporary backward motion are illustrated in Figs. 1.6 and 1.9, respectively. (Courtesy of Erich Lessing/Magnum.)

Fig. 1.5 Curved shadow of Earth This multiple-exposure photograph of a total lunar eclipse reveals the curved shape of the Earth's shadow, regarded by ancient Greek astronomers as evidence that the Earth is a sphere. Only a spherical body will cast the same circular shadow on the Moon when viewed from different locations on Earth or during different lunar eclipses. This photograph was taken by Akira Fujii during the lunar eclipse of 30 December 1982.

As we now know, Aristarchos was right. The stars seem to be revolving about the Earth each night, but appearances can be deceiving. The Earth could instead be spinning beneath the stars. As the Earth rotates, the stars slide by, accounting for the wheeling night sky, which just seems to be revolving.

And the Sun might not be moving across the bright blue sky each day, for the Earth's rotation could produce this motion. Every point on the surface of a spinning Earth can be carried across the line of sight to an unmoving Sun, from sunrise to sunset, producing night and day (Fig. 1.7). Since the Earth rotates from west to east, the Sun appears

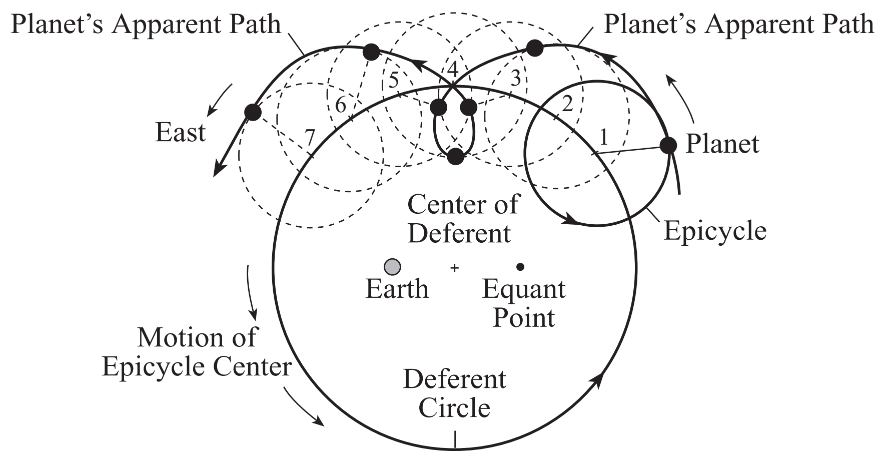

Fig. 1.6 Circles upon circles to explain retrograde loops To explain the occasional retrograde loops in the apparent motions of Mars, Jupiter and Saturn, astronomers in ancient times imagined that each planet travels with uniform speed around a small circle, known as the epicycle. The epicycle's center moves uniformly on a larger circle, the deferent. A similar scheme was used by Ptolemy (fl. 150 AD) to explain the wayward motions of the planets in his *Almagest*. In the Ptolemaic system, the Earth was displaced from the center of the large circle, and each planet traveled with uniform motion with respect to another imaginary point, the equant, appearing to move with variable speed when viewed from the Earth.

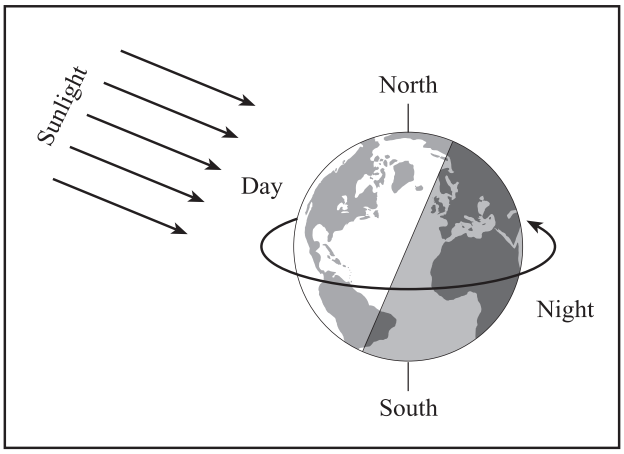

Fig. 1.7 Night and day The Earth rotates with respect to the Sun once every 24 hours, causing the sequence of night and day. Each point on the Earth's surface moves in a circular track parallel to the equator, and each track spends a different time in the Sun depending on the season. This drawing depicts summer in the northern hemisphere and winter in the southern hemisphere. Because the northern part of the Earth's rotational axis is tipped toward the Sun, circular tracks in the northern hemisphere spend a longer time in the Sun than southern ones.

to rise in the east and set in the west. Such a perspective involves a certain amount of detachment – the ability to separate yourself from the ground and use your mind's eye to look down on the spherical, rotating Earth, like a spinning ball suspended in space.

The Moon's motion from horizon to horizon each night could also be neatly explained by the rotation of the Earth, and the Moon's monthly circuit against the background stars could be ascribed to its slower orbital motion around the Earth. This would also account for the Moon's varying appearance (Fig. 1.8). The Moon borrows its light from the Sun, and the Sun illuminates first one part of the Moon's face and then another as the Moon orbits the Earth. On any given night, all observers on Earth will see the same phase of the Moon as our planet's rotation brings it into view.

The concept of a moving Earth nevertheless seems to violate common sense. The ground certainly seems to be at rest beneath our feet, providing the terra firma on which we carry out our daily lives. As Aristotle noticed, an arrow shot vertically upward falls to the ground where the archer stands, suggesting that the ground has not moved while the arrow was in flight. Moreover, if the Earth is rotating, then its surface regions have to be moving at high speeds (Focus 1.1).

Yet the globe on which we live might not only spin on its axis; it could also be whirling ceaselessly around the Sun, completing one circuit each year as Aristarchos had supposed. But his proposals had little impact on his contemporaries. It took another eighteen centuries before the Polish cleric and astronomer Mikolaj Kopernik (1473–1543), better known as Nicolaus Copernicus, revived this heliocentric, or Sun-centered, model. By 1514 Copernicus was privately circulating a manuscript, the *Commentariolus*, or *Little Commentary*, in which the planets were placed in uniform motion about a central Sun. His longer, more influential book, *De Revolutionibus Orbium Coelestium Libri VI*, or *Six Books Concerning the Revolutions of the Celestial*

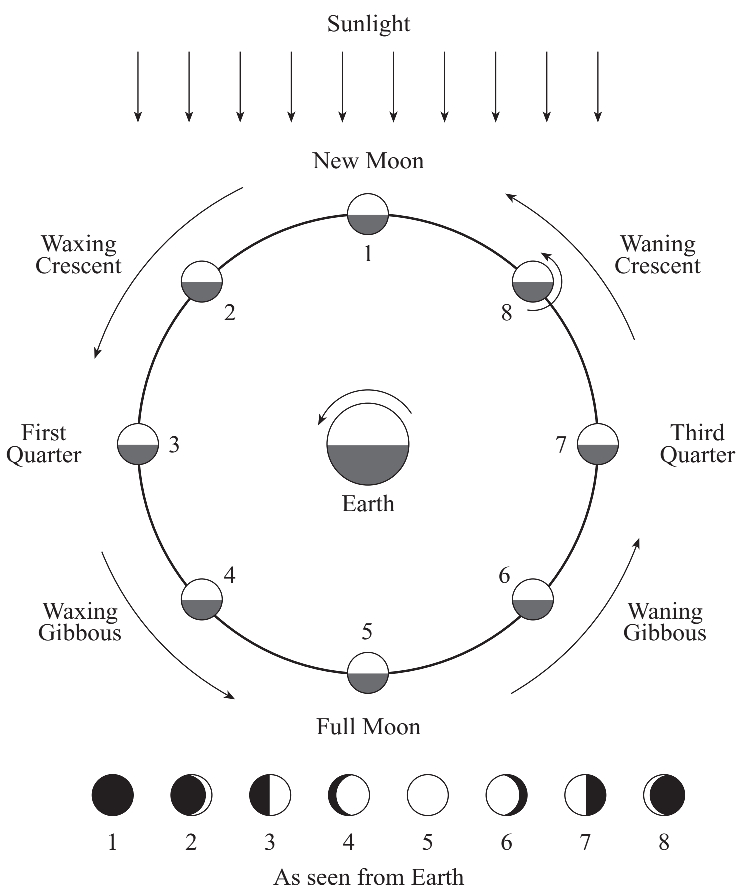

Fig. 1.8 Phases of the Moon Light from the Sun illuminates one half of the Moon, while the other half is dark. As the Moon orbits the Earth, we see varying amounts of its illuminated surface. The phases seen by an observer on Earth (*bottom*) correspond to the numbered points along the lunar orbit. The period from new Moon to new Moon is 29.53 days, the length of the month. As the Earth completes its daily rotation, all night-time observers see the same phase of the Moon.

Focus 1.1 Location and rotation speed on the Earth

The length of the day and the rotation period is the same for every place on Earth, but the speed of rotation around its axis depends on the surface location. A grid of great circles on the spherical Earth defines this location. A great circle divides the sphere in half, and the name comes from the fact that no greater circles can be drawn on a sphere. A great circle halfway between the North and South Poles is called the equator, because it is equally distant between both poles. Circles of longitude are great circles that pass around the Earth from pole to pole perpendicular to the equator, with 0 degrees at the Prime Meridian that passes through the Royal Observatory in Greenwich, England. The latitude is the angle measured northward (positive) or southward (negative) along a circle of longitude from the equator to the point.

The surface speed of rotation is greatest at the equator and reduces to almost nothing at the poles. Using an equatorial radius of about 6378 kilometers, which is close to the value inferred long ago (by Eratosthenes about 200 BC), the Earth would have to be rotating at a velocity of about 460 meters per second to spin about its equatorial circumference once every 24 hours. To calculate this speed, just multiply the equatorial radius by 2π to get the equatorial circumference, and divide by 24 hours and 3600 seconds per hour. At higher latitudes, closer to the poles, the circumferential distance around the Earth, and perpendicular to a great circle of longitude, is less, so the speed is less. The speed diminishes to almost nothing at the geographic poles, which are pierced by the rotation axis.

Bodies, was published almost thirty years later, in 1543, the year of its author's death.

For Copernicus, the Sun was located at the heart of the planetary system and the center of the Universe. The only thing to orbit the Earth was the Moon, and the Earth was supposed to rotate on its axis to make the stars swing by. In this model, the Earth was just one of several planets revolving around the Sun, in the same direction but at different distances and with various speeds, always passing each other without ever intersecting. In order of increasing