Peter Bond

SOLAR SURVEYORS

Observing the Sun from Space

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To David Calvert, who has been circling the Sun for the past 40 years.

Principal Scientific Units

The units used in this book are taken from the original source material. Some sources use the International System of Units (Systeme International, SI), but many astronomers use the centimeter-gram-second (c.g.s.) units. The reader may want to refer to this table of the principal SI units and their equivalent centimeter-gram-second (c.g.s.) units. For example, one nanometer = 10^{-9} meters or one billionth of a meter. One nanometer = 10 Angstroms.

Quantity	**SI Units**	**c.g.s Units**
Wavelength	Nanometer (nm) = 10^{-9} m	1 Angstrom (Å) = 10^{-10} m
Frequency	Hertz (Hz)	
Mass	Kilogram (kg)	1,000 grams (g)
Energy*	Joule (J)	10 million erg
Power	Watt (W) = 1 Joule per second	10 million erg per second
Magnetic flux density	Tesla (T)	10,000 Gauss (G)

- The energy of high-energy particles and X-ray radiation is often expressed in units of kilo-electron volts (keV = 1,000 electron volts) or mega-electron volts (MeV – one million electron volts), where 1 electron volt is equal to 1.6 x 10^{-19}Joules.
- The SI unit of frequency is the hertz (Hz), defined as one cycle per second. Hertz are commonly expressed in multiples: kilohertz (10 Hz, kHz), megahertz (10 Hz, MHz), gigahertz (10 Hz, GHz), terahertz (10 Hz, THz) etc. 1 Hz = 299,792,458 m.

Acknowledgments

This book is the product of many years of research in my capacity as editor of the Jane's Space Systems & Industry reference work, as the Space Science Advisor for the Royal Astronomical Society and as a writer about space activities.

Over several decades, I have received tremendous help from scientists and public relations officers at numerous space agencies and companies around the world, especially NASA and ESA. Most of the images in the book have originated with these two agencies.

Particular mention must be made of Juha-Pekka Luntama, Head of the Space Weather Office at ESA, who provided information about the forthcoming Lagrange mission (now known as ESA Vigil) and spared the time to give me an interview.

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Thanks also to David Harland for his thorough editing of the draft text, and to my wife, Edna, who has supported my efforts during the lengthy writing process.

Preface

The Sun is our nearest star, a mere 150 million km away. Located in one of the spiral arms of the Milky Way, the Sun occupies a quiet suburban neighborhood, far from the star-packed galactic center.

On a cosmic scale, the Sun is very small, ordinary star, but it dominates our tiny corner of the Milky Way. All of the planets in the Solar System could easily fit inside its huge gaseous sphere. Its enormous gravity holds onto a retinue of eight planets, hundreds of dwarf planets and moons, and millions of comets and asteroids. The charged particles of the solar wind penetrate far beyond the outermost planet, Neptune, while its gravitational influence extends far into interstellar space.

We depend upon the Sun for the light and heat that make life on Earth possible. If the Sun should suddenly be extinguished, our planet would rapidly transform into a lifeless, frigid snowball.

The Sun has been shining for billions of years, and it will continue to shine for billions of years into the future. Yet our nearest star is not unchanging: its familiar 11-year cycle of sunspot activity has been recorded since long before the invention of the telescope.

Changes also occur on much longer time scales. Soon after its birth in a collapsing cloud of gas and dust, the Sun was much colder than it is today. Now, some five billion years later, it has evolved into a small, unspectacular star, one of hundreds of billions in our Milky Way galaxy.

However, as its hydrogen fuel is consumed by nuclear fusion, the Sun will gradually become even hotter and begin to expand until it becomes a red giant, swallowing the inner planets of the Solar System, and, perhaps, Earth itself. Even if our world escapes this immersion, the huge star that will dominate the sky will cause the oceans to boil away so that Earth will become a searingly hot, barren desert.

Fortunately for us, the Sun largely avoids the major tantrums observed on other stars. Even so, astronauts and satellites are vulnerable if exposed to sudden eruptions of energetic particles and radiation from solar flares, as well as billion-ton clouds of ionized gas, known as coronal mass ejections.

Although the planet's atmosphere shields us from most of the harmful radiation emitted by our nearby star, we are nearly all familiar with the potential for developing skin cancer from over-exposure to solar ultraviolet light.

Our modern technology-dependent civilization is also vulnerable to solar storms, with the possibility of radio blackouts and power cuts, along with damage to the satellites that provide our navigation signals and broadband communications.

The most extreme geomagnetic storm yet recorded, the Carrington event of 1859, shut down telegraph lines and created dazzling auroral displays around the globe. If such a powerful storm should interact with our planet today, the disruption to our power and computer systems would be immense.

This book tells the story of how, over the centuries, we have striven to observe and understand our neighboring star and its impact on the space around it, particularly our home planet.

The first chapter summarizes early ideas about the Sun and its significance to ancient civilizations, who could only wonder about the nature of this brilliant object that dominated the daylight hours. Small wonder that the Sun was worshipped as a god and stone monuments were constructed to mark the passing of the seasons.

Chapter two describes how, with the introduction of new scientific instruments and modern knowledge of nuclear physics, we have come to a much greater understanding of the huge ball of plasma that dominates our part of the Galaxy. For example, we now largely understand how the Sun's vast output of energy is generated in a dense core where the temperature soars to 15 million degrees Celsius.

However, mysteries still remain, most notably the existence of a multi-million-degree atmosphere – the corona – above a relatively balmy surface layer where the temperature is less than 6,000 degrees Celsius.

As the title indicates, most of the book is devoted to the numerous satellites and space observatories that have been launched over the past six decades to explore the Sun, its expanding atmosphere – the solar wind - and its influence on interplanetary space. In these chapters I have attempted to describe all of the relevant space missions and to summarize their contributions to our knowledge of this fascinating object.

The most detailed and important observations have often come from large space observatories equipped with a battery of scientific instruments. Some of these missions have been delivered to orbit by crewed spacecraft, most notably the Space Shuttle. The largest spacecraft ever to observe the Sun was the US Skylab space station, which was equipped with the first large telescope designed to study the X-ray Sun. In many ways, Skylab marked the beginning of modern solar studies.

Perhaps the most remarkable of the solar space observatories is the ESA-NASA Solar and Heliospheric Observatory (SOHO), which is still operational after more than 26 years in orbit. During its lifetime, scientific instrumentation and observational capabilities have improved by leaps and bounds, but SOHO's discoveries remain a foundation for more advanced spacecraft.

I have also included a chapter on ground-based observatories - some of which provide key information on solar activity – as well as small payloads and innovative instruments that have been flown on balloons and suborbital sounding rockets. These low-cost projects may offer little more than brief snapshots of the turbulent Sun, but they often pave the way for instruments that are subsequently flown on orbital missions.

The book concludes with a look at future missions. Some of these involve miniaturized satellites, known as CubeSats, that can be developed quickly and relatively cheaply with limited, specific objectives in mind. Others are ambitious, multi-instrumented observatories that will be deployed in stable orbits at the so-called Lagrange points, 1.5 million km from Earth.

This book appears at an exciting time for solar explorers. The latest additions to the armada of international spacecraft that are staring continuously at the Sun – the Parker Solar Probe and Solar Orbiter – are currently moving closer to our star than any previous missions. The Parker Solar Probe has already made history by flying through the Sun's outer atmosphere – the corona - and sampling its sea of ionized gas and magnetic fields. Many new discoveries await.

Peter Bond
Cranleigh, England
January 2022

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1

Getting To Know The Sun

1.1 WANDERING STARS

Since time immemorial, people have stared in wonder at the sky. In addition to the familiar, twinkling stars, observers noted seven objects that moved with varying speeds against the background of ‘fixed’ stars. In order of greatest apparent brightness, they were the Sun, Moon, Venus, Jupiter, Mars, Mercury and Saturn. The ancient Greeks called them “planetes” (“wandering stars”), a designation we still use for all but the Sun and Moon.

The primary task of ancient astrologers and astronomers – the two disciplines were inextricably intertwined for many centuries – was to keep track of the movements of the Sun, Moon and planets, and to predict the future by using these movements as signs and portents.

The most important of the wanderers were the Sun, which was responsible for daylight, and the Moon, which dominated the night. Both of these objects displayed visible disks and moved quite rapidly across the sky.

Careful study of their regular motions and apparitions enabled people to devise calendars and introduce convenient ways of measuring time. Thus, a year was the period of time before the Sun returned to the same place in the sky, while a month was the period that elapsed between each new or full Moon.

In many ancient civilizations, the Sun was worshipped as a god. Perhaps the best known is the Egypt of the pharaohs, where the Sun god Re was the dominant figure. According to myth, the Sun god traveled across the heavenly ocean each day, then traveled beneath the Earth during the night before reappearing the next morning. The Sun began its journey as the young god Khepri appeared in the zenith at noon as the full-grown Sun, Re, and reached the west during the evening as the old Sun god, Atum.

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In the Indian sub-continent and the pre-Columbian civilizations of Mexico and Peru, Sun worship was a prominent feature. The Aztecs believed that extensive human sacrifice was demanded by the Sun gods Huitzilopochtli and Tezcatlipoca. The ruler in Peru was regarded as an incarnation of the Sun god, Inti. In Japan the Sun goddess, Amaterasu, was considered to be the supreme ruler of the world and the deity linked to the imperial clan. To this day the Sun symbols represent the Japanese state.

1.2 KEEPING TIME

The regular sequence of days and nights is the most familiar phenomenon associated with the Sun and its apparent movement across the sky. Each day, the Sun rises in the east and sets in the west. This knowledge, of enormous value to ancient travelers and sailors, is the basis of all systems of time keeping.

However, this is a generalization. Careful observation shows that the positions of sunrise and sunset on the horizon change day by day. The times at which these events occur also change daily.

The irregular pattern of day and night duration is linked to Earth's seasons. Away from the equator, people noticed a cold season when the Sun was low in the sky and days were short (winter). Conversely, they experienced a warm or hot season (summer), when the Sun rose high in the sky and days were much longer.

The changing seasons were of prime importance to ancient agrarian cultures whose survival depended upon successful harvests. There were various methods by which time was measured, based on the movements of celestial bodies.

The most fundamental of these was the year, which was determined by watching how the length of the day and the height of the Sun above the horizon changed over time. On midwinter's day, the Sun would be at its lowest in the sky and the period of daylight would reach a minimum. Half a year later, the opposite would apply. The period of time between each midsummer's day was known as one year.

Even before clocks were invented, it was possible to count the number of days in a year – typically 365 – although it increased to 366 every 4 years or so. Over a long period of time, it was possible to calculate that the average length of a year was about 365¼ days. This eventually led to the introduction of a leap year once every four years in order to keep solar time synchronized with actual time.

Various structures were built across the globe to mark key events in the solar calendar, such as the spring and autumn equinoxes (when the length of day and night is the same) and the solstices (midsummer's day and midwinter's day).

Figure 1.1: The Sun rising behind the Heel Stone at Stonehenge, shortly after sunrise on the summer solstice (midsummer's day). (Andrew Dunn/Wikimedia) https://commons.wikimedia.org/wiki/File:Sun_behind_the_Heel_Stone.jpg

Perhaps the most famous is the megalithic stone circle at Stonehenge in England, where people still flock to witness the rising of the Sun between two standing stones on midsummer's day.

Less grandiose ways to mark the passage of time and key days in their agricultural calendar were used by other ancient peoples, such as the rising or setting of the Sun behind a particular mountain peak.

The apparent irregular motion of the Sun caused a number of headaches for observers. Curiously, the first half of the year did not last precisely the same length of time as the second half. Apart from the variable length of the year, and the changes in altitude and the direction of the rising and setting Sun, the time of sunrise moved forward by about 4 minutes each day. This led to the recognition that there are two periods of time that may be called "days".

The actual period between one noon and the next (which averages 24 hours) is known as the solar day. However, when its location in the sky is compared with the background of stars, the Sun appears to complete one revolution around Earth approximately every 23 hours 56 minutes. This is known as the sidereal day (Fig. 1.2).

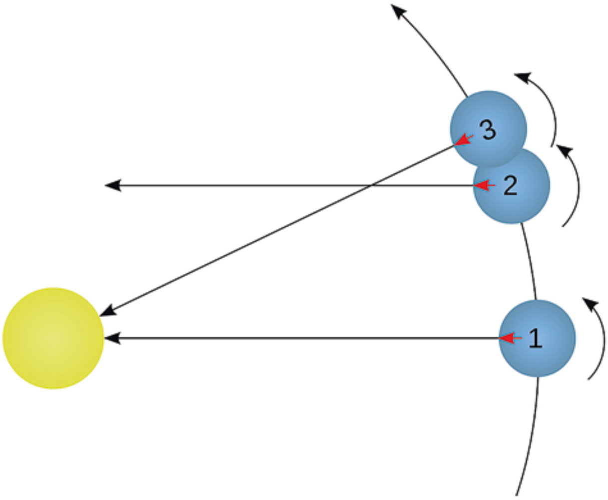

Figure 1.2: Most early observers believed that the Sun orbited Earth. We now know that the reverse is true. In this diagram, the Sun and a distant star are both overhead at noon (1). After Earth has rotated 360°, the distant star is overhead again. The time period between 1 and 2 is the sidereal day – about 23 hours 56 minutes. However, the Sun is not overhead again until Earth has rotated a little further. The interval between 1 and 3 is one solar day of 24 hours. (Wikipedia)

We now know that planets have seasons because their rotational axes are tilted, rather than perpendicular (upright) in relation to the planes of their orbits. Venus and Jupiter have negligible axial inclinations, so there is no difference between the amount of solar radiation arriving at their equator or poles throughout their year. This is not the case with planets such as Earth, Mars and Saturn, which have noticeable tilts.

The northern hemisphere experiences summer when the North Pole is tilted toward the Sun. Six months later, when Earth has traveled halfway around its orbit, the northern hemisphere is tilted away from the Sun and experiences winter (Fig. 1.3). The seasons are reversed in the southern hemisphere.

The dates on which Earth's axis is most directly tilted toward or away from the Sun are known as the solstices. They occur on or around June 21, when the Sun is overhead at midday at the Tropic of Cancer (23.44°N), and December 22, when the midday Sun is overhead at the Tropic of Capricorn (23.44°S).

Not only are days longer in summer, but the Sun moves noticeably higher above the horizon at that time of year, providing more heat per square meter of surface area. The opposite is true in the winter. These two factors combined account for much of the difference in seasonal temperature.

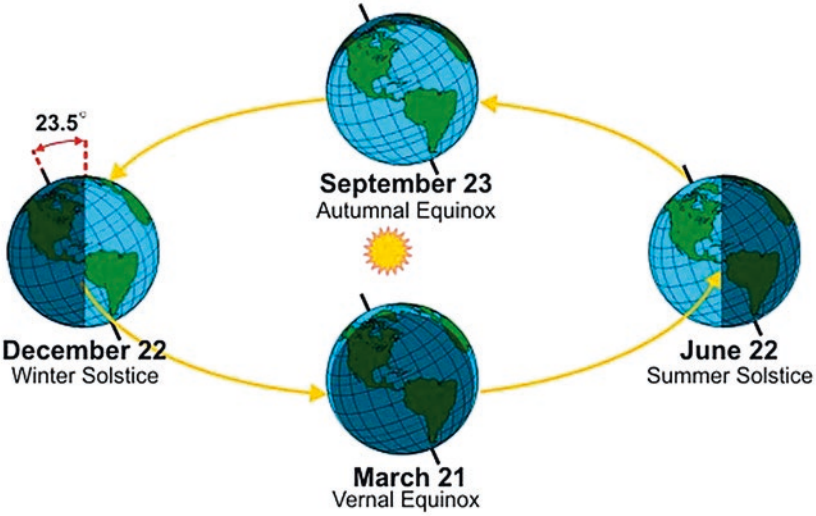

Figure 1.3: Since Earth's axis is inclined to its orbital plane, the amount of radiation any one place receives varies throughout the year. In June, the North Pole is tilted towards the Sun, resulting in longer days and warmer temperatures (i.e. summer) in the northern hemisphere. In December, the North Pole is tilted away from the Sun, causing longer nights and colder temperatures (winter) in the northern hemisphere. The seasons are reversed in the southern hemisphere. (NOAA)

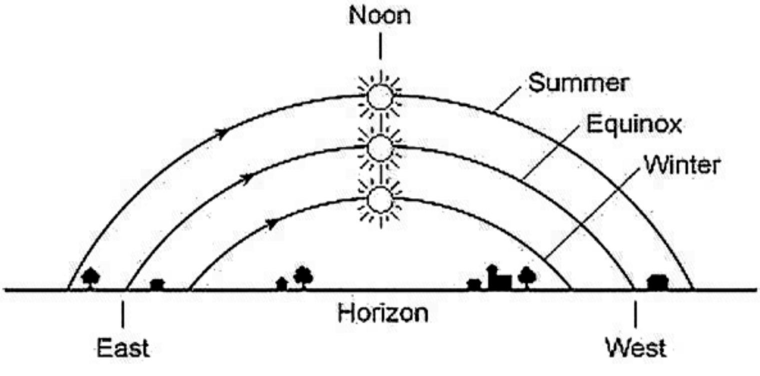

Figure 1.4: The Sun's motion across the sky, looking south. The maximum height of the Sun in the sky, and its rising and setting points on the horizon, change with the seasons. In summer, the Sun rises in the north east, reaches its highest maximum height at noon, and stays up longest. The Sun rises in the south east 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 (20 March) and on the autumnal equinox (23 September) when the Sun rises exactly east and sets exactly west. (NASA)

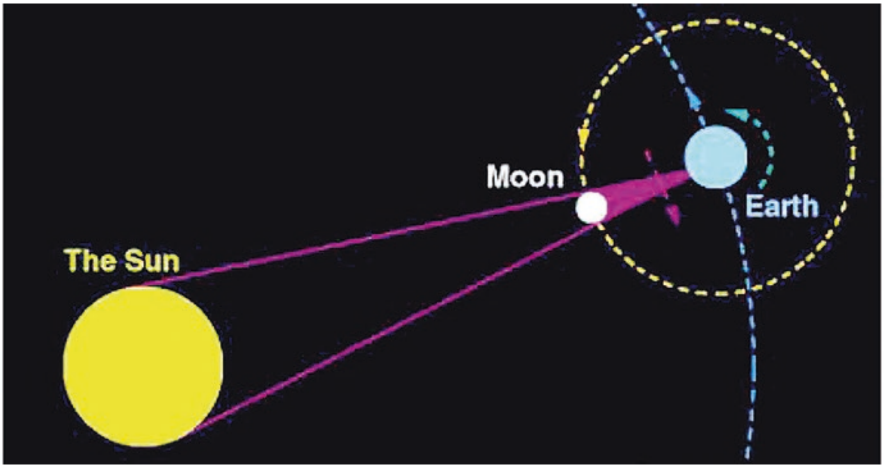

Figure 1.5: Once every four weeks, the Moon moves between the Sun and Earth. This is the lunar phase known as New Moon. Occasionally, the Moon passes precisely in front of the Sun, so that the satellite's shadow (the umbra) just reaches Earth. This results in a total solar eclipse for anyone located within the umbra. As the shadow travels across the surface of the rotating Earth, it traces a narrow path of totality, where the Sun's disk is hidden from view for up to 7½ minutes. (ESA)

When one of the poles is tilted towards the Sun, the surrounding regions at high latitude are bathed in permanent sunlight (hence the term, "the land of the midnight Sun"). The opposite polar region endures 24-hour darkness and extreme cold.

However, the noonday Sun is never far from the zenith at the equator, so the amount of solar radiation (insolation) received shows little variation throughout the year. Hence, the equatorial regions are always hot.

Midway between the solstices, on or around 21 March and 23 September, the Sun is directly overhead at noon at the equator. On those dates, Earth's axis is inclined away from the Sun. Day and night are equal in length across the globe, so they are known as the spring (or vernal) and autumnal equinoxes.

Earth's orbit is slightly elliptical. The planet is closest to the Sun (perihelion) in early January, about two weeks after the December solstice. This means that the northern hemisphere winter and the southern hemisphere summer begin about the time that Earth is nearest the Sun. (Similarly, the southern hemisphere's winter and northern hemisphere's summer coincide with aphelion.)

However, the difference between the aphelion and perihelion distances is only about 5 million km or 0.3%. This difference results in a 6% increase in insolation from July to January – too small to cause any significant seasonal effects.

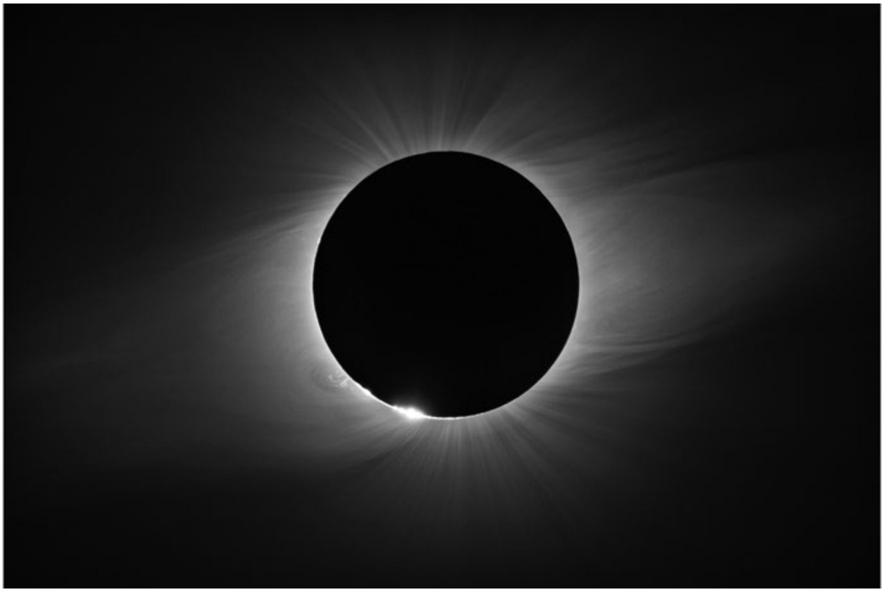

Figure 1.6: On 2 July 2019, a total solar eclipse was visible from ESO's La Silla Observatory in Chile. This image shows the Sun completely covered by the Moon during totality, revealing the solar corona. At the bottom is a "diamond ring" where sunlight is shining through a gap in the lunar mountains. (ESO/P. Horálek)

1.3 SOLAR ECLIPSES

Observation of the Sun usually requires specialized equipment and proper eye protection. However, there are rare occasions when anyone can stare at the Sun (or at least its outer regions) for several minutes without any protection. These spectacular apparitions are total solar eclipses.

Solar eclipses occur when the Moon passes directly in front of the Sun, covering its disk. This is possible because of a mathematical coincidence: the diameter of the Sun is some 400 times greater than the Moon's diameter, but, at this particular epoch of time, the Moon is approximately 400 times closer to Earth than the Sun.

Solar eclipses can only happen at the time of New Moon. If the Moon travels directly between the Sun and Earth, our planet will pass through the lunar shadow and an eclipse will occur. However, such alignments do not take place every 4 weeks, partly because the plane of the Moon's orbit is inclined around 5° to the plane of Earth's orbit. Moreover, although the Moon crosses the plane of Earth's orbit twice every 4 weeks, one of these intersection points (nodes) must intersect a line joining the Sun and Earth for a solar eclipse to occur.

This means that, although the Moon passes between the Sun and Earth during each New Moon phase, the objects are usually not precisely aligned. As a result, there are only two to five total eclipses per year, when the Moon completely covers the Sun's disk.

At such times, the Moon's cone-shaped shadow (the umbra) stretches across space and grazes the Earth. For an observer situated inside the umbra, the eclipse is total. For someone located in the outer part of the shadow (the penumbra), only part of the Sun is masked, so the eclipse is partial.

As the planet rotates, the tip of the umbra travels over the surface at about 1,600 km/h, tracing a path no more than 270 km wide. Within the path of totality the sky goes dark, enabling the stars and planets to appear for up to 7½ minutes.[1]

Just before the Moon completely covers the photosphere, the Sun's light shines through gaps in lunar mountains to produce a glittering "diamond ring" effect. As totality sets in, the normally invisible solar atmosphere – the corona – appears as a pearl-white ring around the black Moon.[2]

The visible structure of the corona is related to the density of electrons in the solar atmosphere that are available to reflect light from the photosphere. Its appearance varies considerably. Near times of solar maximum, when sunspots are most numerous, the corona displays numerous bright "helmet" streamers that emanate all around the solar disk. When the Sun is less active, these streamers are fewer in number, and often missing altogether from the polar regions.

A number of reddish, flame-like prominences may rise above the lunar limb, held in place by powerful magnetic fields. Meanwhile, the sky turns dark, allowing the stars and planets to appear. Birds stop singing as the brief "night" takes hold. Then, as the eclipse comes to a close, a bright "diamond ring" effect may reappear on the Moon's limb.

Sometimes, when the Moon is near its apogee, the lunar disk does not completely cover the Sun. During such an annular eclipse, the Moon's umbral shadow does not reach Earth, so the dark circle of the Moon is surrounded by a bright ring.[3] Annular eclipses are slightly more frequent than total eclipses.

Partial eclipses are seen over a much larger area than total eclipses, so they are much more frequent in any given location on Earth. At these times, only part of the Sun is covered by the Moon, resembling a bite taken out of its disk.

---

[1] The longest total eclipse of the 21st century, which took place over Asia on 22 July 2009, lasted a maximum of 6 minutes 39 seconds. This duration will not be exceeded until 2132.

[2] The corona is not usually visible in daylight because its luminosity is only about one millionth that of the photosphere.

[3] Annular comes from *annulus*, the Latin word for "ring".

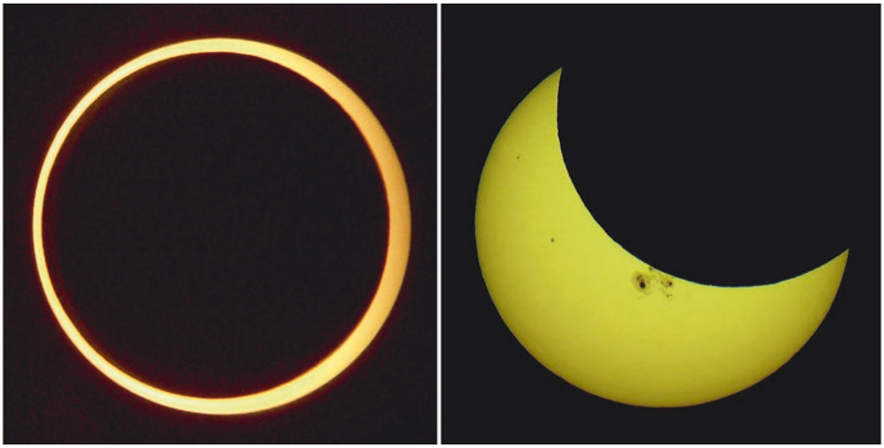

Figure 1.7: (a) An annular eclipse which took place on 30 May 2012, as seen from Middlegate, Nevada. (b) A partial solar eclipse photographed on 23 October 2014. Note the sunspots to the left of the Moon's disk. (Wikimedia) https://commons.wikimedia.org/wiki/File:Annular_Eclipse._Taken_from_Middlegate,_Nevada_on_May_20,_2012.jpg https://commons.wikimedia.org/wiki/File:Partial_solar_eclipse_Oct_23_2014_Minneapolis_5-36pm_Ruen1.png

1.4 SIZE AND DISTANCE

Early observers soon noted that the Sun and planets often came together in the sky or even passed behind the Moon during occultations. They always remained within a narrow band on the sky, known as the zodiac (after the Greek word for "animal"). The Sun's annual path across the sky, called the ecliptic, ran along the center of this celestial highway. Clearly, the planes of the planets' orbits were closely aligned with each other.

Solar eclipses, when the Sun gradually disappeared from view behind the Moon, were particularly significant. Some ancient civilizations, such as the Chinese, believed such eclipses were caused by a dragon eating the Sun. One story tells how two astrologers, Hi and Ho, failed to warn the emperor that such a significant event was about to happen, and they paid for their negligence with their heads.

Clearly, the Moon must be closer to Earth than the Sun, since it occasionally covered the Sun's disk as it passed in front of it (see Section 1.3).

Sometimes, however, the Moon only partially covered the Sun, so that a ring of sunlight was still visible (an annular eclipse). This was evidence that the distances between the Earth, Sun and Moon were not always the same. Furthermore, the

Moon often appeared to take a bite out of the brilliant Sun. Clearly, in such a partial eclipse the objects were not in perfect alignment (Fig. 1.7).

On other occasions, the fully illuminated Moon was darkened as it passed through Earth's shadow. Such lunar eclipses only took place at the time of Full Moon, when Earth lay directly between the Sun and Moon.

Ancient observers did not require advanced instrumentation to show that the Sun and Moon appear to be much larger than any celestial objects beyond Earth. Furthermore, they appear to be very similar in size, a property confirmed during total solar eclipses.

However, since the Moon always passes in front of the Sun during a solar eclipse, it is clearly closer to Earth than our brilliant star. The problem for ancient astronomers was to determine the actual distances of these two objects, as well as their true sizes.

The first step was the realization by early observers that lunar eclipses were caused by Earth's shadow. By measuring the radius of the curved shadow on the lunar surface, the Greek mathematician Aristarchus (c.310-c.230 BC) was able to use simple geometry to calculate that Earth's radius is approximately four times greater than that of the Moon.

He also estimated that the Moon's average distance was about 70 Earth radii, though he seems never to have attempted to translate this into an actual distance.

A little over a century later, another Greek astronomer, Hipparchus (c.190-c.120 BC), refined this method to determine that the distance of the Moon from Earth was between 59 and 67 Earth radii.

Meanwhile, another Greek mathematician, Eratosthenes (c.276-c.196 BC), had been able to calculate Earth's circumference and radius by measuring the length of the Sun's shadow at noon in two widely space locations (Alexandria and Syene) at the time of the spring equinox (when the midday Sun was directly overhead at the Tropic of Cancer). By simple trigonometry he could then derive Earth's diameter.

Unfortunately, other observers came up with smaller dimensions, and it was these that were passed on by the Greek astronomer Claudius Ptolemy and that were accepted by scholars all over the world for the next 1,400 years.

This error had important consequences: when Christopher Columbus sailed west from Spain in search of a new route to Asia, he did so in the belief that it was only about 5,000-6,000 km distant. If he had known that the true distance was about 17,000 km, it is unlikely that he would ever have proposed such an expedition or received sponsorship. Fortunately, he encountered the Americas where he thought Asia would be.

Although Aristarchus and Hipparchus produced excellent estimates for the size and distance of the Moon, the Sun remained a much more challenging object.

Clearly, the Sun was much further away than the Moon, but obtaining a reasonable approximation of its distance was extremely difficult.

The best method available to the ancient Greeks involved studies of the Moon and Sun at times of "half Moon", i.e. the phases known as first quarter and last quarter. Aware that the Moon appears half illuminated by sunlight during these phases, Aristarchus reasoned that, at such times, the Sun-Moon-Earth angle must be 90°.

By measuring the angle between the Moon and Sun as seen from Earth, he could once again use trigonometry to determine the ratio of the distance of the Moon and Sun (Fig. 1.8). Unfortunately, measurements of angles in the sky are difficult to obtain without precision instruments and determining the actual time of first or last quarter is also not easy.

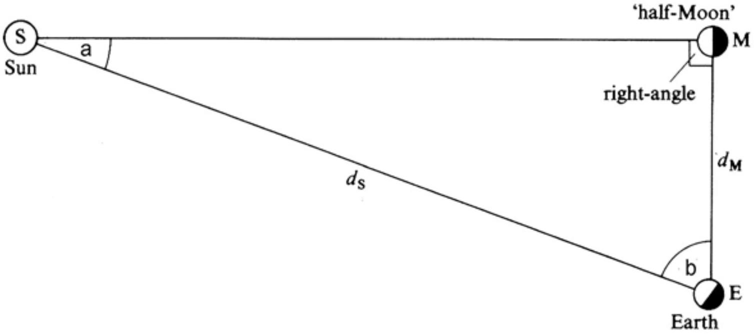

Figure 1.8: Aristarchus estimated the distance of the Sun by attempting to measure the angle between the Moon and Sun at the time when exactly half of the Moon was illuminated. At such times sunlight must be striking the Moon at 90° (a right angle). If the angles in the Sun-Earth-Moon triangle are known, the distance of the Sun (ds) can be calculated using trigonometry. Aristarchus estimated that angle 'b' was 87°, so angle 'a' (exaggerated here) must be 3°. This enabled him to calculate the relative lengths of the sides of the triangle. (Peter Bond)

Aristarchus measured the Sun-Earth-Moon angle to be 87°, whereas it is actually 89.85°.

Although his method was mathematically sound, the errors in his measurements meant that his results were wildly inaccurate.

Aristarchus concluded that that the Sun was about 20 times as distant as the Moon, and hence 20 times the diameter of the Moon – explaining the ability of the tiny Moon to precisely cover the huge Sun during a total eclipse. We now know that the Sun is 400 times further than our natural satellite, and, therefore, 400 times wider. Nevertheless, his efforts indicated that the universe was much larger than previously thought.

The determination of the true scale of the Solar System had to wait until the 17th century, following the invention of the telescope and various instruments that could measure angles with precision, together with a recognition that the Sun, and not Earth, lay at the center of our planetary system.

The basic geometrical method they used was called parallax. This involved measurement of the apparent shift in position of an object when viewed from two different locations. To illustrate this, hold one finger upright in front of your nose and close first one eye and then the other. The finger seems to shift position against the background, although it is, of course, stationary. When the finger is moved closer, the shift appears larger, and vice versa.

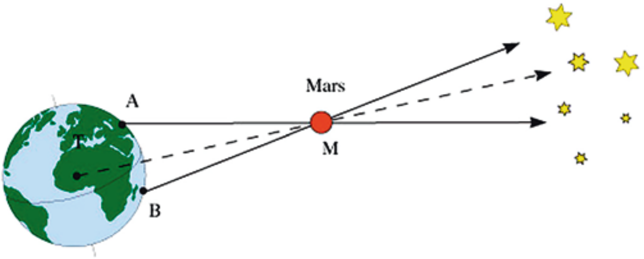

Figure 1.9: The distance of a planet such as Mars can be calculated by measuring its angle of sight - its location against the background of fixed stars - from two or more widely separated places on Earth. If the length of the baseline (e.g. the distance between two viewing sites, A-B) is known, the distance can be found by simple trigonometry. By using Kepler's third law, the length of the mean Sun-Earth distance – known as the astronomical unit – can be calculated. (ESO)

Astronomers realized that, if a parallax shift in a planet's position could be measured from two widely separated locations, then its distance could be calculated. This method was first used by a French astronomer, Jean Richer, working in Cayenne (French Guiana) together with Giovanni Domenico Cassini and Jean Picard in Paris. They made simultaneous parallax observations of Mars during its closest approach in 1671, using the recently invented pendulum clocks to ensure that the measurements were made at precisely the same moment.

Cassini's calculations led to a value of about 140 million km for the astronomical unit (AU) – the mean Sun-Earth distance. Now that this distance was known with reasonable accuracy, Kepler's third law (see Section 1.5) could be used to calculate the distances of the planets for the first time. It also enabled the diameter of the Sun to be calculated from its apparent angular size.

During the 18th and 19th centuries a great deal of time, money and effort was spent in attempting to refine these figures. One method was to observe rare transits of Venus across the face of the Sun from many different locations. The most famous transit observations took place in 1761 and 1769 when the British explorer, Captain James Cook, sailed to the Pacific as part of an army of 150 observers scattered across the globe, but the timings of the start and end of the transits proved very difficult, leading to inaccurate results.

More successful was the world-wide effort to determine the parallax of the asteroid Eros when it passed close to Earth in 1931. Highly accurate measurements were possible since Eros has no atmosphere and appears as a mere point of light in even the largest telescopes. The value of the astronomical unit turned out to be about 149.6 million km.

Since then, more sophisticated techniques have been introduced to refine the scale of the Solar System. One of the most successful is radar, when radio signals are reflected from the surfaces of distant objects, such as Venus and passing asteroids. Since the velocity of these microwaves is known (i.e. the speed of light) and the time taken between emission and reception can be measured to a fraction of a second, the distance can be readily calculated.

1.5 THE EARTH-CENTERED UNIVERSE

Until the mid-16th century, most civilizations accepted what their eyes seemed to tell them: that Earth, created by divine beings as the home of humanity, lay at the center of the universe.

The reasons for this thinking seemed self-evident. All celestial objects, including the Sun, moved across the sky from east to west (with the occasional exception of a comet or shooting star). However, since no one experienced any of the sensations that would be expected if Earth was continually spinning, it seemed logical to believe that it was the stars and planets which were in motion around Earth.

According to this geocentric theory, the Sun, Moon and planets were carried by invisible, crystalline spheres which moved around the central Earth. A much larger celestial sphere carried the fixed stars around the central Earth once every day.

It soon became clear that some planets move more slowly through the constellations of the night sky than others. Since a slow-moving planet such as Saturn was also fainter than faster-moving objects such as Mars and Jupiter, the obvious conclusion was that Saturn is further away from Earth.

However, observers soon noted that the planets did not follow simple curved paths across the sky. One of the most difficult observations to explain was an occasional "loop" in the motions of the more distant planets. Each planet would cease its normal eastward movement and then reverse direction toward the west, before eventually resuming its general movement toward the east. This occurred when Mars, Jupiter and Saturn were shining brightly around midnight.

Ancient astronomers resorted to increasingly complex orbital loops, known as epicycles, to account for this peculiar behavior. As time went by, the number of circles was increased so that they more or less accounted for the apparent motions of the planets.

Meanwhile, it was generally accepted that Earth was located at the center of the universe. For 1,400 years, the prevailing astronomical model of the universe in Europe was the Ptolemaic System, a geocentric model published by Claudius Ptolemy in his *Almagest*, written about 140 AD (Fig. 1.10).

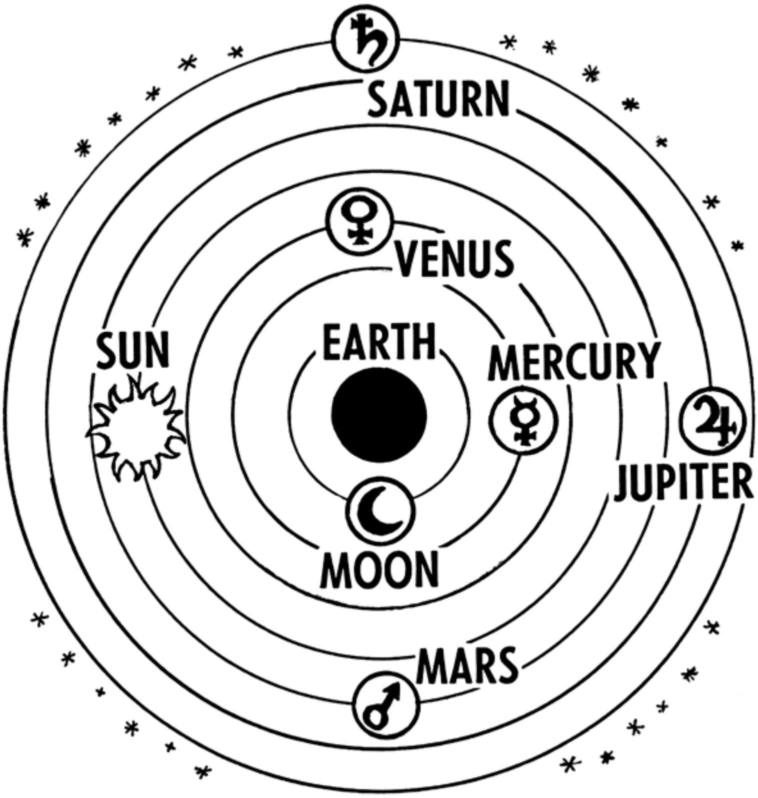

Figure 1.10: Claudius Ptolemy's geocentric system, based on the work of earlier Greek astronomers, was the accepted model of the universe for some 1,400 years. It envisaged a stationary Earth as the center of the universe, around which the Sun, Moon, planets and stars all moved in circular orbits

One rebel was Aristarchus, who took the bold step of placing the Sun at the center of the universe, so that all of the stars and planets, including Earth, moved around it. His revolutionary ideas were widely denounced and Aristarchus barely escaped with his life. The geocentric theory remained at the heart of scientific and religious doctrine for another 1,800 years.

The breakthrough was made by a Polish priest and astronomer named Nicolaus Copernicus (1473-1543). He realized that the only way to make sense of the planetary motions was to relegate Earth to the status of a planet that orbited the Sun (Fig. 1.11). The movement of the stars across the sky was then explained by the rotation of the spherical Earth, while the calendar of seasons and changing constellations in the heavens were accounted for by its year-long journey around the Sun.

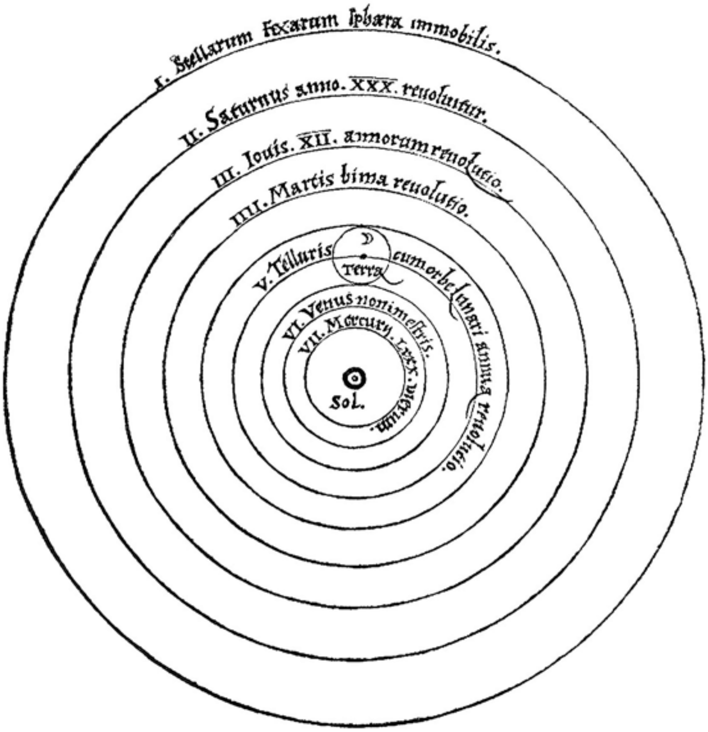

Figure 1.11: Nicolaus Copernicus proposed a heliocentric system which placed the Sun at the center of the universe. All of the planets (including Earth), moved around the Sun in circular orbits. Only the Moon still orbited Earth

Afraid of the consequences of contradicting established doctrine, Copernicus delayed the publication of his most significant work, *De Revolutionibus Orbium*