Astronomy

An overview

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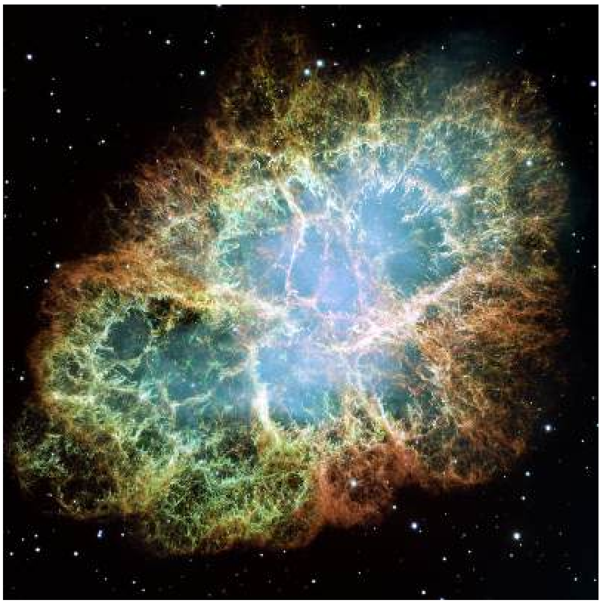
Main article

Astronomy

Astronomy is a natural science that deals with the study of celestial objects (such as stars, planets, comets, nebulae, star clusters and galaxies) and phenomena that originate outside the Earth's atmosphere (such as the cosmic background radiation). It is concerned with the evolution, physics, chemistry, meteorology, and motion of celestial objects, as well as the formation and development of the universe.



A giant Hubble mosaic of the Crab Nebula, a supernova remnant

Astronomy is one of the oldest sciences. Prehistoric cultures left behind astronomical artifacts such as the Egyptian monuments and Stonehenge, and early civilizations such as the Babylonians, Greeks, Chinese, Indians, and Maya performed methodical observations of the night sky. However, the invention of the telescope was required before astronomy was able to develop into a modern science. Historically, astronomy has included disciplines as diverse as astrometry, celestial navigation, observational astronomy, the making of calendars, and even astrology, but professional astronomy is nowadays often considered to be synonymous with astrophysics.

During the 20th century, the field of professional astronomy split into observational and theoretical branches. Observational astronomy is focused on acquiring data from observations of celestial objects, which is then analyzed using basic principles of physics. Theoretical astronomy is oriented towards the development of computer or analytical models to describe astronomical objects and phenomena. The two fields complement each other, with theoretical astronomy seeking to explain the observational results, and observations being used to confirm theoretical results.

Amateur astronomers have contributed to many important astronomical discoveries, and astronomy is one of the few sciences where amateurs can still play an active role, especially in the discovery and observation of transient phenomena.

Ancient astronomy is not to be confused with astrology, the belief system which claims that human affairs are correlated with the positions of celestial objects. Although the two fields share a common origin and a part of their methods (namely, the use of ephemerides), they are distinct.[1]

Lexicology

The word *astronomy* (from the Greek words *astron* (*ἄστρον*), "star" and -nomy from *nomos* (*νόμος*), "law" or "culture") literally means "law of the stars" (or "culture of the stars" depending on the translation).

Use of terms "astronomy" and "astrophysics"

Generally, either the term "astronomy" or "astrophysics" may be used to refer to this subject.[2] [3] [4] Based on strict dictionary definitions, "astronomy" refers to "the study of objects and matter outside the Earth's atmosphere and of their physical and chemical properties"[5] and "astrophysics" refers to the branch of astronomy dealing with "the behavior, physical properties, and dynamic processes of celestial objects and phenomena".[6] In some cases, as in the introduction of the introductory textbook *The Physical Universe* by Frank Shu, "astronomy" may be used to describe the qualitative study of the subject, whereas "astrophysics" is used to describe the physics-oriented version of the subject.[7] However, since most modern astronomical research deals with subjects related to physics, modern astronomy could actually be called astrophysics.[2] Various departments that research this subject may use "astronomy" and "astrophysics", partly depending on whether the department is historically affiliated with a physics department,[3] and many professional astronomers actually have physics degrees.[4] One of the leading scientific journals in the field is named Astronomy and Astrophysics.

History

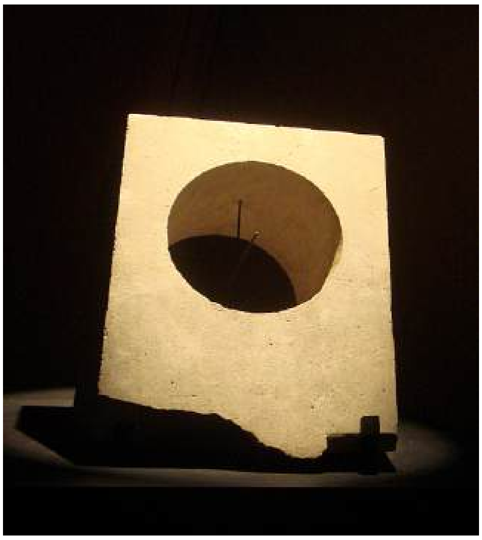
In early times, astronomy only comprised the observation and predictions of the motions of objects visible to the naked eye. In some locations, such as Stonehenge, early cultures assembled massive artifacts that likely had some astronomical purpose. In addition to their ceremonial uses, these observatories could be employed to determine the seasons, an important factor in knowing when to plant crops, as well as in understanding the length of the year.[8]

A celestial map from the 17th century, by the Dutch cartographer Frederik de Wit.

Before tools such as the telescope were invented early study of the stars had to be conducted from the only vantage points available, namely tall buildings and high ground using the naked eye. As civilizations developed, most notably in Mesopotamia, China, Egypt, Greece, India, and Central America, astronomical observatories were assembled, and ideas on the nature of the universe began to be explored. Most of early astronomy actually consisted of mapping the positions of the stars and planets, a science now referred to as astrometry. From these observations, early ideas about the motions of the planets were formed, and the nature of the Sun, Moon and the Earth in the universe were explored philosophically. The Earth was believed to be the center of the universe with the Sun, the Moon and the stars rotating around it. This is known as the geocentric model of the universe.

A particularly important early development was the beginning of mathematical and scientific astronomy, which began among the Babylonians, who laid the foundations for the later astronomical traditions that developed in many other civilizations.[9] The Babylonians discovered that lunar eclipses recurred in a repeating cycle known as a saros.[10]

Following the Babylonians, significant advances in astronomy were made in ancient Greece and the Hellenistic world. Greek astronomy is characterized from the start by seeking a rational, physical explanation for celestial phenomena.[11] In the 3rd century BC, Aristarchus of Samos calculated the size of the Earth, and measured the size and distance of the Moon and Sun, and was the first to propose a heliocentric model of the solar system. In the 2nd century BC, Hipparchus discovered precession, calculated the size and distance of the Moon and invented the earliest known astronomical devices such as the astrolabe.[12] Hipparchus also created a comprehensive catalog of 1020 stars, and most of the constellations of the northern hemisphere derive are taken from Greek astronomy.[13] The Antikythera mechanism (c. 150–80 BC) was an early analog computer designed to calculating the location of the Sun, Moon, and planets for a given date. Technological artifacts of similar complexity did not reappear until the 14th century, when mechanical astronomical clocks appeared in Europe.[14]

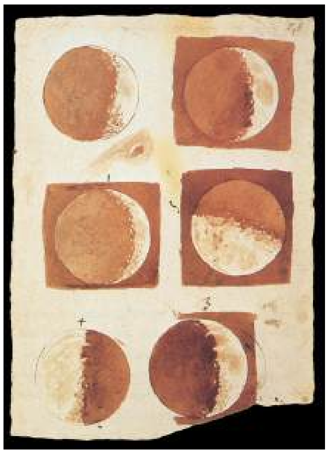


Greek equatorial sun dial, Alexandria on the Oxus, present-day Afghanistan 3rd-2nd century BCE.

During the Middle Ages, astronomy was mostly stagnant in medieval Europe, at least until the 13th century. However, astronomy flourished in the Islamic world and other parts of the world. This led to the emergence of the first astronomical observatories in the Muslim world by the early 9th century.[15] [16] [17] In 964, the Andromeda Galaxy, the nearest galaxy to the Milky Way, was discovered by the Persian astronomer Azophi and first described in his *Book of Fixed Stars*.[18] The SN 1006 supernova, the brightest apparent magnitude stellar event in recorded history, was observed by the Egyptian Arabic astronomer Ali ibn Ridwan and the Chinese astronomers in 1006. Some of the prominent Islamic (mostly Persian and Arab) astronomers who made significant contributions to the science include Al-Battani, Thebit, Azophi, Albumasar, Biruni, Arzachel, Al-Birjandi, and the astronomers of the Maragheh and Samarkand observatories. Astronomers during that time introduced many Arabic names now used for individual stars.[19] [20] It is also believed that the ruins at Great Zimbabwe and Timbuktu[21] may have housed an astronomical observatory.[22] Europeans had previously believed that there had been no astronomical observation in pre-colonial Middle Ages sub-Saharan Africa but modern discoveries show otherwise.[23] [24] [25]

Scientific revolution

During the Renaissance, Nicolaus Copernicus proposed a heliocentric model of the solar system. His work was defended, expanded upon, and corrected by Galileo Galilei and Johannes Kepler. Galileo innovated by using telescopes to enhance his observations.[26]



Galileo's sketches and observations of the Moon revealed that the surface was mountainous.

Kepler was the first to devise a system that described correctly the details of the motion of the planets with the Sun at the center. However, Kepler did not succeed in formulating a theory behind the laws he wrote down.[27] It was left to Newton's invention of celestial dynamics and his law of gravitation to finally explain the motions of the planets. Newton also developed the reflecting telescope.[26]

Further discoveries paralleled the improvements in the size and quality of the telescope. More extensive star catalogues were produced by Lacaille. The astronomer William Herschel made a detailed catalog of nebulosity and clusters, and in 1781 discovered the planet Uranus, the first new planet found.[28] The distance to a star was first announced in 1838 when the parallax of 61 Cygni was measured by Friedrich Bessel.[29]

During the 18–19th centuries, attention to the three body problem by Euler, Clairaut, and D'Alembert led to more accurate predictions about the motions of the Moon and planets. This work was further refined by Lagrange and Laplace, allowing the masses of the planets and moons to be estimated from their perturbations.[30]

Significant advances in astronomy came about with the introduction of new technology, including the spectroscope and photography. Fraunhofer discovered about 600 bands in the spectrum of the Sun in 1814–15, which, in 1859, Kirchhoff ascribed to the presence of different elements. Stars were proven to be similar to the Earth's own Sun, but with a wide range of temperatures, masses, and sizes.[19]

The existence of the Earth's galaxy, the Milky Way, as a separate group of stars, was only proved in the 20th century, along with the existence of "external" galaxies, and soon after, the expansion of the Universe, seen in the recession of most galaxies from us.[31] Modern astronomy has also discovered many exotic objects such as quasars, pulsars, blazars, and radio galaxies, and has used these observations to develop physical theories which describe some of these objects in terms of equally exotic objects such as black holes and neutron stars. Physical cosmology made huge advances during the 20th century, with the model of the Big Bang heavily supported by the evidence provided by astronomy and physics, such as the cosmic microwave background radiation, Hubble's law, and cosmological abundances of elements.

Observational astronomy

The Very Large Array in New Mexico, an example of a radio telescope

In astronomy, the main source of information about celestial bodies and other objects is the visible light or more generally electromagnetic radiation.[32] Observational astronomy may be divided according to the observed region of the electromagnetic spectrum. Some parts of the spectrum can be observed from the Earth's surface, while other parts are only observable from either high altitudes or space. Specific information on these subfields is given below.

Radio astronomy

Radio astronomy studies radiation with wavelengths greater than approximately one millimeter.[33] Radio astronomy is different from most other forms of observational astronomy in that the observed radio waves can be treated as waves rather than as discrete photons. Hence, it is relatively easier to measure both the amplitude and phase of radio waves, whereas this is not as easily done at shorter wavelengths.[33]

Although some radio waves are produced by astronomical objects in the form of thermal emission, most of the radio emission that is observed from Earth is seen in the form of synchrotron radiation, which is produced when electrons oscillate around magnetic fields.[33] Additionally, a number of spectral lines produced by interstellar gas, notably the hydrogen spectral line at 21 cm, are observable at radio wavelengths.[7] [33]

A wide variety of objects are observable at radio wavelengths, including supernovae, interstellar gas, pulsars, and active galactic nuclei.[7] [33]

Infrared astronomy

Infrared astronomy deals with the detection and analysis of infrared radiation (wavelengths longer than red light). Except at wavelengths close to visible light, infrared radiation is heavily absorbed by the atmosphere, and the atmosphere produces significant infrared emission. Consequently, infrared observatories have to be located in high, dry places or in space. The infrared spectrum is useful for studying objects that are too cold to radiate visible light, such as planets and circumstellar disks. Longer infrared wavelengths can also penetrate clouds of dust that block visible light, allowing observation of young stars in molecular clouds and the cores of galaxies.[34] Some molecules radiate strongly in the infrared. This can be used to study chemistry in space; more specifically it can detect water in comets.[35]

Optical astronomy

The Subaru Telescope (left) and Keck Observatory (center) on Mauna Kea, both examples of an observatory that operates at near-infrared and visible wavelengths. The NASA Infrared Telescope Facility (right) is an example of a telescope that operates only at near-infrared wavelengths.

Historically, optical astronomy, also called visible light astronomy, is the oldest form of astronomy.[36] Optical images were originally drawn by hand. In the late 19th century and most of the 20th century, images were made using photographic equipment. Modern images are made using digital detectors, particularly detectors using charge-coupled devices (CCDs). Although visible light itself extends from approximately 4000 Å to 7000 Å (400 nm to 700 nm),[36] the same equipment used at these wavelengths is also used to observe some near-ultraviolet and near-infrared radiation.

Ultraviolet astronomy

Ultraviolet astronomy is generally used to refer to observations at ultraviolet wavelengths between approximately 100 and 3200 Å (10 to 320 nm).[33] Light at these wavelengths is absorbed by the Earth's atmosphere, so observations at these wavelengths must be performed from the upper atmosphere or from space. Ultraviolet astronomy is best suited to the study of thermal radiation and spectral emission lines from hot blue stars (OB stars) that are very bright in this wave band. This includes the blue stars in other galaxies, which have been the targets of several ultraviolet surveys. Other objects commonly observed in ultraviolet light include planetary nebulae, supernova remnants, and active galactic nuclei.[33] However, as ultraviolet light is easily absorbed by interstellar dust, an appropriate adjustment of ultraviolet measurements is necessary.[33]

X-ray astronomy

X-ray astronomy is the study of astronomical objects at X-ray wavelengths. Typically, objects emit X-ray radiation as synchrotron emission (produced by electrons oscillating around magnetic field lines), thermal emission from thin gases above 10^7 (10 million) kelvins, and thermal emission from thick gases above 10^7 Kelvin.[33] Since X-rays are absorbed by the Earth's atmosphere, all X-ray observations must be performed from high-altitude balloons, rockets, or spacecraft. Notable X-ray sources include X-ray binaries, pulsars, supernova remnants, elliptical galaxies, clusters of galaxies, and active galactic nuclei.[33]

According to NASA's official website, X-rays were first observed and documented in 1895 by Wilhelm Conrad Röntgen, a German scientist who found them quite by accident when experimenting with vacuum tubes. Through a series of experiments, including the infamous X-ray photograph he took of his wife's hand with a wedding ring on it, Röntgen was able to discover the beginning elements of radiation. The "X", in fact, holds its own significance, as it represents Röntgen's inability to identify exactly what type of radiation it was.

Furthermore, according to the website, in some German speaking countries, X-rays are still sometimes referred to as Röntgen rays, in honor of the man who discovered them.

Gamma-ray astronomy

Gamma ray astronomy is the study of astronomical objects at the shortest wavelengths of the electromagnetic spectrum. Gamma rays may be observed directly by satellites such as the Compton Gamma Ray Observatory or by specialized telescopes called atmospheric Cherenkov telescopes.[33] The Cherenkov telescopes do not actually detect the gamma rays directly but instead detect the flashes of visible light produced when gamma rays are absorbed by the Earth's atmosphere.[37]

Most gamma-ray emitting sources are actually gamma-ray bursts, objects which only produce gamma radiation for a few milliseconds to thousands of seconds before fading away. Only 10% of gamma-ray sources are non-transient sources. These steady gamma-ray emitters include pulsars, neutron stars, and black hole candidates such as active galactic nuclei.[33]

Fields not based on the electromagnetic spectrum

In addition to electromagnetic radiation, a few other events originating from great distances may be observed from the Earth.

In neutrino astronomy, astronomers use special underground facilities such as SAGE, GALLEX, and Kamioka II/III for detecting neutrinos. These neutrinos originate primarily from the Sun but also from supernovae.[33] Cosmic rays, which consist of very high energy particles that can decay or be absorbed when they enter the Earth's atmosphere, result in a cascade of particles which can be detected by current observatories.[38] Additionally, some future neutrino detectors may also be sensitive to the particles produced when cosmic rays hit the Earth's atmosphere.[33] Gravitational wave astronomy is an emerging new field of astronomy which aims to use gravitational wave detectors to collect observational data about compact objects. A few observatories have been constructed, such as the *Laser Interferometer Gravitational Observatory* LIGO, but gravitational waves are extremely difficult to detect.[39]

Planetary astronomers have directly observed many of these phenomena through spacecraft and sample return missions. These observations include fly-by missions with remote sensors, landing vehicles that can perform experiments on the surface materials, impactors that allow remote sensing of buried material, and sample return missions that allow direct laboratory examination.

Astrometry and celestial mechanics

One of the oldest fields in astronomy, and in all of science, is the measurement of the positions of celestial objects. Historically, accurate knowledge of the positions of the Sun, Moon, planets and stars has been essential in celestial navigation and in the making of calendars.

Careful measurement of the positions of the planets has led to a solid understanding of gravitational perturbations, and an ability to determine past and future positions of the planets with great accuracy, a field known as celestial mechanics. More recently the tracking of near-Earth objects will allow for predictions of close encounters, and potential collisions, with the Earth.[40]

The measurement of stellar parallax of nearby stars provides a fundamental baseline in the cosmic distance ladder that is used to measure the scale of the universe. Parallax measurements of nearby stars provide an absolute baseline for the properties of more distant stars, because their properties can be compared. Measurements of radial velocity and proper motion show the kinematics of these systems through the Milky Way galaxy. Astrometric results are also used to measure the distribution of dark matter in the galaxy.[41]

During the 1990s, the astrometric technique of measuring the stellar wobble was used to detect large extrasolar planets orbiting nearby stars.[42]

Theoretical astronomy

Theoretical astronomers use a wide variety of tools which include analytical models (for example, polytropes to approximate the behaviors of a star) and computational numerical simulations. Each has some advantages. Analytical models of a process are generally better for giving insight into the heart of what is going on. Numerical models can reveal the existence of phenomena and effects that would otherwise not be seen.[43] [44]

Theorists in astronomy endeavor to create theoretical models and figure out the observational consequences of those models. This helps observers look for data that can refute a model or help in choosing between several alternate or conflicting models.

Theorists also try to generate or modify models to take into account new data. In the case of an inconsistency, the general tendency is to try to make minimal modifications to the model to fit the data. In some cases, a large amount of inconsistent data over time may lead to total abandonment of a model.

Topics studied by theoretical astronomers include: stellar dynamics and evolution; galaxy formation; large-scale structure of matter in the Universe; origin of cosmic rays; general relativity and physical cosmology, including string cosmology and astroparticle physics. Astrophysical relativity serves as a tool to gauge the properties of large scale structures for which gravitation plays a significant role in physical phenomena investigated and as the basis for black hole (*astro*)physics and the study of gravitational waves.

Some widely accepted and studied theories and models in astronomy, now included in the Lambda-CDM model are the Big Bang, Cosmic inflation, dark matter, and fundamental theories of physics.

A few examples of this process:

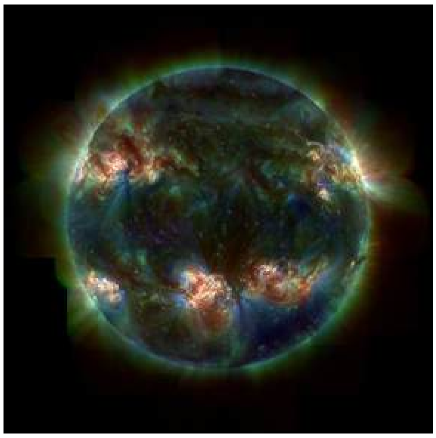
Physical process	Experimental tool	Theoretical model	Explains/predicts
Gravitation	Radio telescopes	Self-gravitating system	Emergence of a star system
Nuclear fusion	Spectroscopy	Stellar evolution	How the stars shine and how metals formed
The Big Bang	Hubble Space Telescope, COBE	Expanding universe	Age of the Universe
Quantum fluctuations		Cosmic inflation	Flatness problem
Gravitational collapse	X-ray astronomy	General relativity	Black holes at the center of Andromeda galaxy
CNO cycle in stars			

Dark matter and dark energy are the current leading topics in astronomy,[45] as their discovery and controversy originated during the study of the galaxies.

Specific subfields

Solar astronomy

At a distance of about eight light-minutes, the most frequently studied star is the Sun, a typical main-sequence dwarf star of stellar class G2 V, and about 4.6 Gyr in age. The Sun is not considered a variable star, but it does undergo periodic changes in activity known as the sunspot cycle. This is an 11-year fluctuation in sunspot numbers. Sunspots are regions of lower-than- average temperatures that are associated with intense magnetic activity.[46]



An ultraviolet image of the Sun's active photosphere as viewed by the TRACE space telescope. *NASA photo*

The Sun has steadily increased in luminosity over the course of its life, increasing by 40% since it first became a main-sequence star. The Sun has also undergone periodic changes in luminosity that can have a significant impact on the Earth.[47] The Maunder minimum, for example, is believed to have caused the Little Ice Age phenomenon during the Middle Ages.[48]

The visible outer surface of the Sun is called the photosphere. Above this layer is a thin region known as the chromosphere. This is surrounded by a transition region of rapidly increasing temperatures, then by the super-heated corona.

At the center of the Sun is the core region, a volume of sufficient temperature and pressure for nuclear fusion to occur. Above the core is the radiation zone, where the plasma conveys the energy flux by means of radiation. The outer layers form a convection zone where the gas material transports energy primarily through physical displacement of the gas. It is believed that this convection zone creates the magnetic activity that generates sun spots.[46]

A solar wind of plasma particles constantly streams outward from the Sun until it reaches the heliopause. This solar wind interacts with the magnetosphere of the Earth to create the Van Allen radiation belts, as well as the aurora where the lines of the Earth's magnetic field descend into the atmosphere.[49]

Planetary science

This astronomical field examines the assemblage of planets, moons, dwarf planets, comets, asteroids, and other bodies orbiting the Sun, as well as extrasolar planets. The solar system has been relatively well-studied, initially through telescopes and then later by spacecraft. This has provided a good overall understanding of the formation and evolution of this planetary system, although many new discoveries are still being made.[50]

The black spot at the top is a dust devil climbing a crater wall on Mars. This moving, swirling column of Martian atmosphere (comparable to a terrestrial tornado) created the long, dark streak. *NASA image*.

The solar system is subdivided into the inner planets, the asteroid belt, and the outer planets. The inner terrestrial planets consist of Mercury, Venus, Earth, and Mars. The outer gas giant planets are Jupiter, Saturn, Uranus, and Neptune.[51] Beyond Neptune lies the Kuiper Belt, and finally the Oort Cloud, which may extend as far as a light-year.

The planets were formed in the protoplanetary disk that surrounded the early Sun. Through a process that included gravitational attraction, collision, and accretion, the disk formed clumps of matter that, with time, became protoplanets. The radiation pressure of the solar wind then expelled most of the unaccreted matter, and only those planets with sufficient mass retained their gaseous atmosphere. The planets continued to sweep up, or eject, the remaining matter during a period of intense bombardment, evidenced by the many impact craters on the Moon. During this period, some of the protoplanets may have collided, the leading hypothesis for how the Moon was formed.[52]

Once a planet reaches sufficient mass, the materials with different densities segregate within, during planetary differentiation. This process can form a stony or metallic core, surrounded by a mantle and an outer surface. The core may include solid and liquid regions, and some planetary cores generate their own magnetic field, which can protect their atmospheres from solar wind stripping.[53]

A planet or moon's interior heat is produced from the collisions that created the body, radioactive materials (*e.g.* uranium, thorium, and ^{26}Al), or tidal heating. Some planets and moons accumulate enough heat to drive geologic processes such as volcanism and tectonics. Those that accumulate or retain an atmosphere can also undergo surface erosion from wind or water. Smaller bodies, without tidal heating, cool more quickly; and their geological activity ceases with the exception of impact cratering.[54]

Stellar astronomy

The study of stars and stellar evolution is fundamental to our understanding of the universe. The astrophysics of stars has been determined through observation and theoretical understanding; and from computer simulations of the interior.[55]

The Ant planetary nebula. Ejecting gas from the dying central star shows symmetrical patterns unlike the chaotic patterns of ordinary explosions.

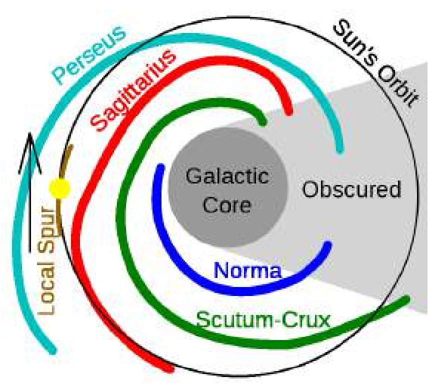
Star formation occurs in dense regions of dust and gas, known as giant molecular clouds. When destabilized, cloud fragments can collapse under the influence of gravity, to form a protostar. A sufficiently dense, and hot, core region will trigger nuclear fusion, thus creating a main-sequence star.[56]

Almost all elements heavier than hydrogen and helium were created inside the cores of stars.[55]

The characteristics of the resulting star depend primarily upon its starting mass. The more massive the star, the greater its luminosity, and the more rapidly it expends the hydrogen fuel in its core. Over time, this hydrogen fuel is completely converted into helium, and the star begins to evolve. The fusion of helium requires a higher core temperature, so that the star both expands in size, and increases in core density. The resulting red giant enjoys a brief life span, before the helium fuel is in turn consumed. Very massive stars can also undergo a series of decreasing evolutionary phases, as they fuse increasingly heavier elements.[57]

The final fate of the star depends on its mass, with stars of mass greater than about eight times the Sun becoming core collapse supernovae;[58] while smaller stars form planetary nebulae, and evolve into white dwarfs.[59] The remnant of a supernova is a dense neutron star, or, if the stellar mass was at least three times that of the Sun, a black hole.[60] Close binary stars can follow more complex evolutionary paths, such as mass transfer onto a white dwarf companion that can potentially cause a supernova.[61] Planetary nebulae and supernovae are necessary for the distribution of metals to the interstellar medium; without them, all new stars (and their planetary systems) would be formed from hydrogen and helium alone.[62]

Galactic astronomy



Observed structure of the Milky Way's spiral arms

Our solar system orbits within the Milky Way, a barred spiral galaxy that is a prominent member of the Local Group of galaxies. It is a rotating mass of gas, dust, stars and other objects, held together by mutual gravitational attraction. As the Earth is located within the dusty outer arms, there are large portions of the Milky Way that are obscured from view.

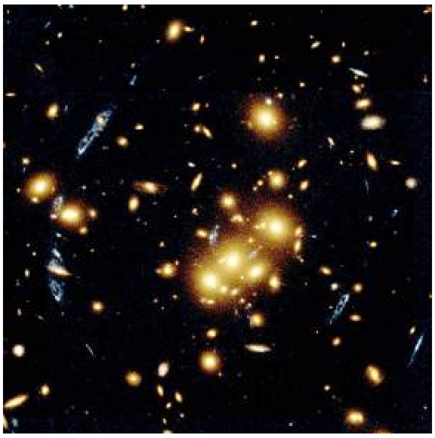
In the center of the Milky Way is the core, a bar-shaped bulge with what is believed to be a supermassive black hole at the center. This is surrounded by four primary arms that spiral from the core. This is a region of active star formation that contains many younger, population I stars. The disk is surrounded by a spheroid halo of older, population II stars, as well as relatively dense concentrations of stars known as globular clusters.[63] [64]

Between the stars lies the interstellar medium, a region of sparse matter. In the densest regions, molecular clouds of molecular hydrogen and other elements create star-forming regions. These begin as a compact pre-stellar core or dark nebulae, which concentrate and collapse (in volumes determined by the Jeans length) to form compact protostars.[56]

As the more massive stars appear, they transform the cloud into an H II region of glowing gas and plasma. The stellar wind and supernova explosions from these stars eventually serve to disperse the cloud, often leaving behind one or more young open clusters of stars. These clusters gradually disperse, and the stars join the population of the Milky Way.[65]

Kinematic studies of matter in the Milky Way and other galaxies have demonstrated that there is more mass than can be accounted for by visible matter. A dark matter halo appears to dominate the mass, although the nature of this dark matter remains undetermined.[66]

Extragalactic astronomy



This image shows several blue, loop-shaped objects that are multiple images of the same galaxy, duplicated by the gravitational lens effect of the cluster of yellow galaxies near the middle of the photograph. The lens is produced by the cluster's gravitational field that bends light to magnify and distort the image of a more distant object.

The study of objects outside our galaxy is a branch of astronomy concerned with the formation and evolution of Galaxies; their morphology and classification; and the examination of active galaxies, and the groups and clusters of galaxies. The latter is important for the understanding of the large-scale structure of the cosmos.

Most galaxies are organized into distinct shapes that allow for classification schemes. They are commonly divided into spiral, elliptical and Irregular galaxies.[67]

As the name suggests, an elliptical galaxy has the cross-sectional shape of an ellipse. The stars move along random orbits with no preferred direction. These galaxies contain little or no interstellar dust; few star-forming regions; and generally older stars. Elliptical galaxies are more commonly found at the core of galactic clusters, and may be formed through mergers of large galaxies.

A spiral galaxy is organized into a flat, rotating disk, usually with a prominent bulge or bar at the center, and trailing bright arms that spiral outward. The arms are dusty regions of star formation where massive young stars produce a blue tint. Spiral galaxies are typically surrounded by a halo of older stars. Both the Milky Way and the Andromeda Galaxy are spiral galaxies.

Irregular galaxies are chaotic in appearance, and are neither spiral nor elliptical. About a quarter of all galaxies are irregular, and the peculiar shapes of such galaxies may be the result of gravitational interaction.

An active galaxy is a formation that is emitting a significant amount of its energy from a source other than stars, dust and gas; and is powered by a compact region at the core, usually thought to be a super-massive black hole that is emitting radiation from in-falling material.

A radio galaxy is an active galaxy that is very luminous in the radio portion of the spectrum, and is emitting immense plumes or lobes of gas. Active galaxies that emit high-energy radiation include Seyfert galaxies, Quasars, and Blazars. Quasars are believed to be the most consistently luminous objects in the known universe.[68]

The large-scale structure of the cosmos is represented by groups and clusters of galaxies. This structure is organized in a hierarchy of groupings, with the largest being the superclusters. The collective matter is formed into filaments and walls, leaving large voids in between.[69]

Cosmology

Cosmology (from the Greek κόσμος "world, universe" and λόγος "word, study") could be considered the study of the universe as a whole.

Observations of the large-scale structure of the universe, a branch known as physical cosmology, have provided a deep understanding of the formation and evolution of the cosmos. Fundamental to modern cosmology is the well-accepted theory of the big bang, wherein our universe began at a single point in time, and thereafter expanded over the course of 13.7 Gyr to its present condition.[70] The concept of the big bang can be traced back to the discovery of the microwave background radiation in 1965.[70]

In the course of this expansion, the universe underwent several evolutionary stages. In the very early moments, it is theorized that the universe experienced a very rapid cosmic inflation, which homogenized the starting conditions. Thereafter, nucleosynthesis produced the elemental abundance of the early universe.[70] (See also nucleocosmochronology.)

When the first atoms formed, space became transparent to radiation, releasing the energy viewed today as the microwave background radiation. The expanding universe then underwent a Dark Age due to the lack of stellar energy sources.[71]

A hierarchical structure of matter began to form from minute variations in the mass density. Matter accumulated in the densest regions, forming clouds of gas and the earliest stars. These massive stars triggered the reionization process and are believed to have created many of the heavy elements in the early universe which tend to decay back to the lighter elements extending the cycle.[72]

Gravitational aggregations clustered into filaments, leaving voids in the gaps. Gradually, organizations of gas and dust merged to form the first primitive galaxies. Over time, these pulled in more matter, and were often organized into groups and clusters of galaxies, then into larger-scale superclusters.[73]

Fundamental to the structure of the universe is the existence of dark matter and dark energy. These are now thought to be the dominant components, forming 96% of the mass of the universe. For this reason, much effort is expended in trying to understand the physics of these components.[74]

Interdisciplinary studies

Astronomy and astrophysics have developed significant interdisciplinary links with other major scientific fields. Archaeoastronomy is the study of ancient or traditional astronomies in their cultural context, utilizing archaeological and anthropological evidence. Astrobiology is the study of the advent and evolution of biological systems in the universe, with particular emphasis on the possibility of non-terrestrial life.

The study of chemicals found in space, including their formation, interaction and destruction, is called astrochemistry. These substances are usually found in molecular clouds, although they may also appear in low temperature stars, brown dwarfs and planets. Cosmochemistry is the study of the chemicals found within the Solar System, including the origins of the elements and variations in the isotope ratios. Both of these fields represent an overlap of the disciplines of astronomy and chemistry. As "forensic astronomy", finally, methods from astronomy have been used to solve problems of law and history.

Amateur astronomy

Astronomy is one of the sciences to which amateurs can contribute the most.[75]

Amateur astronomers can build their own equipment, and can hold star parties and gatherings, such as Stellafane.

Collectively, amateur astronomers observe a variety of celestial objects and phenomena sometimes with equipment that they build themselves. Common targets of amateur astronomers include the Moon, planets, stars, comets, meteor showers, and a variety of deep-sky objects such as star clusters, galaxies, and nebulae. One branch of amateur astronomy, amateur astrophotography, involves the taking of photos of the night sky. Many amateurs like to specialize in the observation of particular objects, types of objects, or types of events which interest them.[76] [77]

Most amateurs work at visible wavelengths, but a small minority experiment with wavelengths outside the visible spectrum. This includes the use of infrared filters on conventional telescopes, and also the use of radio telescopes. The pioneer of amateur radio astronomy was Karl Jansky, who started observing the sky at radio wavelengths in the 1930s. A number of amateur astronomers use either homemade telescopes or use radio telescopes which were originally built for astronomy research but which are now available to amateurs (*e.g.* the One-Mile Telescope).[78] [79]

Amateur astronomers continue to make scientific contributions to the field of astronomy. Indeed, it is one of the few scientific disciplines where amateurs can still make significant contributions. Amateurs can make occultation measurements that are used to refine the orbits of minor planets. They can also discover comets, and perform regular observations of variable stars. Improvements in digital technology have allowed amateurs to make impressive advances in the field of astrophotography.[80] [81] [82]

Major problems

Although the scientific discipline of astronomy has made tremendous strides in understanding the nature of the universe and its contents, there remain some important unanswered questions. Answers to these may require the construction of new ground- and space-based instruments, and possibly new developments in theoretical and experimental physics.

- What is the origin of the stellar mass spectrum? That is, why do astronomers observe the same distribution of stellar masses – the initial mass function – apparently regardless of the initial conditions?[83] A deeper understanding of the formation of stars and planets is needed.
- Is there other life in the Universe? Especially, is there other intelligent life? If so, what is the explanation for the Fermi paradox? The existence of life elsewhere has important scientific and philosophical implications.[84] [85] Is the Solar System normal or atypical?
- What caused the Universe to form? Is the premise of the Fine-tuned universe hypothesis correct? If so, could this be the result of cosmological natural selection? What caused the cosmic inflation that produced our homogeneous universe? Why is there a baryon asymmetry?
- What is the nature of dark matter and dark energy? These dominate the evolution and fate of the cosmos, yet their true nature remains unknown.[86] What will be the ultimate fate of the universe?[87]
- How did the first galaxies form? How did supermassive black holes form?
- What is creating the ultra-high-energy cosmic rays?

International Year of Astronomy 2009

During the 62nd General Assembly of the UN, 2009 was declared to be the International Year of Astronomy (IYA2009), with the resolution being made official on 20 December 2008. A global scheme laid out by the International Astronomical Union (IAU), it was also endorsed by UNESCO – the UN body responsible for Educational, Scientific and Cultural matters. IYA2009 was intended to be a global celebration of astronomy and its contributions to society and culture, stimulating worldwide interest not only in astronomy but science in general, with a particular slant towards young people.

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External links

- International Year of Astronomy 2009 (http://www.astronomy2009.org) IYA2009 Main website
- Cosmic Journey: A History of Scientific Cosmology (http://www.aip.org/history/cosmology/index.htm) from the American Institute of Physics
- Southern Hemisphere Astronomy (http://www.astronomy.net.nz)
- Celestia Motherlode (http://www.celestiamotherlode.net/catalog/educational.php/) Educational site for Astronomical journeys through space
- Astronomy – A History – G. Forbes – 1909 (eLibrary Project – eLib Text) (http://www.literature.at/elib/index.php5?title=Astronomy_-_A_History_-_George_Forbes_-_1909)
- Prof. Sir Harry Kroto, NL (http://www.vega.org.uk/video/subseries/16), Astrophysical Chemistry Lecture Series. 8 Freeview Lectures provided by the Vega Science Trust.
- Core books (http://ads.harvard.edu/books/clab/) and core journals (http://ads.harvard.edu/books/clabj/) in Astronomy, from the Smithsonian/NASA Astrophysics Data System

History

History of astronomy

Astronomy is the oldest of the natural sciences, dating back to antiquity, with its origins in the religious, mythological, and astrological practices of pre-history: vestiges of these are still found in astrology, a discipline long interwoven with public and governmental astronomy, and not completely disentangled from it until a few centuries ago in the Western World (see astrology and astronomy). In some cultures astronomical data was used for astrological prognostication.

Ancient astronomers were able to differentiate between stars and planets, as stars remain relatively fixed over the centuries while planets will move an appreciable amount during a comparatively short time.

Early history

Early cultures identified celestial objects with gods and spirits. They related these objects (and their movements) to phenomena such as rain, drought, seasons, and tides. It is generally believed that the first "professional" astronomers were priests (such as the Magi), and that their understanding of the "heavens" was seen as "divine", hence astronomy's ancient connection to what is now called astrology. Ancient structures with possibly astronomical alignments (such as Stonehenge) probably fulfilled both astronomical and religious functions.

Calendars of the world have usually been set by the Sun and Moon (measuring the day, month and year), and were of importance to agricultural societies, in which the harvest depended on planting at the correct time of year. The most common modern calendar is based on the Roman calendar, which divided the year into twelve months of alternating thirty and thirty-one days apiece. In 46 BC Julius Caesar instigated calendar reform and adopted a calendar based upon the 365 1/4 day year length originally proposed by 4th century BC Greek astronomer Callippus.

Mesopotamia

The origins of Western astronomy can be found in Mesopotamia, the "land between the rivers" Tigris and Euphrates, where the ancient kingdoms of Sumer, Assyria, and Babylonia were located. A form of writing known as cuneiform emerged among the Sumerians around 3500–3000 BC. Our knowledge of Sumerian astronomy is indirect, via the earliest Babylonian star catalogues dating from about 1200 BC. The fact that many star names appear in Sumerian suggests a continuity reaching into the Early Bronze Age. Astral theology, which gave planetary gods an important role in Mesopotamian mythology and religion, began with the Sumerians. They also used a sexagesimal (base 60) place-value number system, which simplified the task of recording very large and very small numbers. The modern practice of dividing a circle into 360 degrees, of 60 minutes each, began with the Sumerians. For more information, see the articles on Babylonian numerals and mathematics.

Classical sources frequently use the term Chaldeans for the astronomers of Mesopotamia, who were, in reality, priest-scribes specializing in astrology and other forms of divination.

The first evidence of recognition that astronomical phenomena are periodic and of the application of mathematics to their prediction is Babylonian. Tablets dating back to the Old Babylonian period document the application of mathematics to the variation in the length of daylight over a solar year. Centuries of Babylonian observations of celestial phenomena are recorded in the series of cuneiform tablets known as the *Enūma Anu Enlil*. The oldest significant astronomical text that we possess is Tablet 63 of the *Enūma Anu Enlil*, the Venus tablet of Ammi-saduqa, which lists the first and last visible risings of Venus over a period of about 21 years and is the earliest evidence that the phenomena of a planet were recognized as periodic. The MUL.APIN, contains catalogues of stars and constellations as well as schemes for predicting heliacal risings and the settings of the planets, lengths of daylight measured by a water-clock, gnomon, shadows, and intercalations. The Babylonian GU text arranges stars in 'strings' that lie along declination circles and thus measure right-ascensions or time-intervals, and also employs the stars of the zenith, which are also separated by given right-ascensional differences.[1]

A significant increase in the quality and frequency of Babylonian observations appeared during the reign of Nabonassar (747–733 BC). The systematic records of ominous phenomena in astronomical diaries that began at this time allowed for the discovery of a repeating 18-year cycle of lunar eclipses, for example. The Greek astronomer Ptolemy later used Nabonassar's reign to fix the beginning of an era, since he felt that the earliest usable observations began at this time.

The last stages in the development of Babylonian astronomy took place during the time of the Seleucid Empire (323–60 BC). In the third century BC, astronomers began to use "goal-year texts" to predict the motions of the planets. These texts compiled records of past observations to find repeating occurrences of ominous phenomena for each planet. About the same time, or shortly afterwards, astronomers created mathematical models that allowed them to predict these phenomena directly, without consulting past records. A notable Babylonian astronomer from this time was Seleucus of Seleucia, who was a supporter of the heliocentric model.

Babylonian astronomy was the basis for much of what was done in Greek and Hellenistic astronomy, in classical Indian astronomy, in Sassanian Iran, in Byzantium, in Syria, in Islamic astronomy, in Central Asia, and in Western Europe.[2]

Egypt

The precise orientation of the Egyptian pyramids affords a lasting demonstration of the high degree of technical skill in watching the heavens attained in the 3rd millennium BC. It has been shown the Pyramids were aligned towards the pole star, which, because of the precession of the equinoxes, was at that time Thuban, a faint star in the constellation of Draco.[3] Evaluation of the site of the temple of Amun-Re at Karnak, taking into account the change over time of the obliquity of the ecliptic, has shown that the Great Temple was aligned on the rising of the midwinter sun.[4] The length of the corridor down which sunlight would travel would have limited illumination at other times of the year.

Astronomy played a considerable part in religious matters for fixing the dates of festivals and determining the hours of the night. The titles of several temple books are preserved recording the movements and phases of the sun, moon and stars. The rising of Sirius (Egyptian: Sopdet, Greek: Sothis) at the beginning of the inundation was a particularly important point to fix in the yearly calendar.

Writing in the Roman era, Clement of Alexandria gives some idea of the importance of astronomical observations to the sacred rites:

> And after the Singer advances the Astrologer (ὡροσκόπος), with a *horologium* (ὡρολόγιον) in his hand, and a *palm* (φοίνιξ), the symbols of astrology. He must know by heart the Hermetic astrological books, which are four in number. Of these, one is about the arrangement of the fixed stars that are visible; one on the positions of the sun and moon and five planets; one on the conjunctions and phases of the sun and moon; and one concerns their risings.[5]

The Astrologer's instruments (*horologium* and *palm*) are a plumb line and sighting instrument. They have been identified with two inscribed objects in the Berlin Museum; a short handle from which a plumb line was hung, and a palm branch with a sight-slit in the broader end. The latter was held close to the eye, the former in the other hand, perhaps at arms length. The "Hermetic" books which Clement refers to are the Egyptian theological texts, which probably have nothing to do with Hellenistic Hermetism.[6]

From the tables of stars on the ceiling of the tombs of Rameses VI and Rameses IX it seems that for fixing the hours of the night a man seated on the ground faced the Astrologer in such a position that the line of observation of the pole star passed over the middle of his head. On the different days of the year each hour was determined by a fixed star culminating or nearly culminating in it, and the position of these stars at the time is given in the tables as in the centre, on the left eye, on the right shoulder, etc. According to the texts, in founding or rebuilding temples the north axis was determined by the same apparatus, and we may conclude that it was the usual one for astronomical observations. In careful hands it might give results of a high degree of accuracy.

Greece and Hellenistic world

The Ancient Greeks developed astronomy, which they treated as a branch of mathematics, to a highly sophisticated level. The first geometrical, three-dimensional models to explain the apparent motion of the planets were developed in the 4th century BC by Eudoxus of Cnidus and Callippus of Cyzicus . Their models were based on nested homocentric spheres centered upon the Earth. Their younger contemporary Heraclides Ponticus proposed that the Earth rotates around its axis.

A different approach to celestial phenomena was taken by natural philosophers such as Plato and Aristotle. They were less concerned with developing mathematical predictive models than with developing an explanation of the reasons for the motions of the Cosmos. In his *Timaeus* Plato described the universe as a spherical body divided into circles carrying the planets and governed according to harmonic intervals by a world soul.[7] Aristotle, drawing on the mathematical model of Eudoxus, proposed that the universe was made of a complex system of concentric spheres, whose circular motions combined to carry the planets around the earth.[8] This basic cosmological model prevailed, in various forms, until the 16th century AD.

Greek geometrical astronomy developed away from the model of concentric spheres to employ more complex models in which an eccentric circle would carry around a smaller circle, called an epicycle which in turn carried around a planet. The first such model is attributed to Apollonius of Perga and further developments in it were carried out in the 2nd century BC by Hipparchus of Nicea. Hipparchus made a number of other contributions, including the first measurement of precession and the compilation of the first star catalog in which he proposed our modern system of apparent magnitudes.

The study of astronomy by the ancient Greeks was not limited to Greece itself but was further developed in the 3rd and 2nd centuries BC, in the Hellenistic states and in particular in Alexandria. However, the work was still done by ethnic Greeks. In the 3rd century BC Aristarchus of Samos was the first to suggest a heliocentric system, although only fragmentary descriptions of his idea survive.[9] Eratosthenes, using the angles of shadows created at widely separated regions, estimated the circumference of the Earth with great accuracy.[10]

The Antikythera mechanism, an ancient Greek astronomical observational device for calculating the movements of the Sun and the Moon, possibly the planets, dates from about 150-100 BC, and was the first ancestor of an astronomical computer. It was discovered in an ancient shipwreck off the Greek island of Antikythera, between Kythera and Crete. The device became famous for its use of a differential gear, previously believed to have been invented in the 16th century AD, and the miniaturization and complexity of its parts, comparable to a clock made in the 18th century. The original mechanism is displayed in the Bronze collection of the National Archaeological Museum of Athens, accompanied by a replica.

Depending on the historian's viewpoint, the acme or corruption of physical Greek astronomy is seen with Ptolemy of Alexandria, who wrote the classic comprehensive presentation of geocentric astronomy, the *Megale Syntaxis* (Great Synthesis), better known by its Arabic title *Almagest*, which had a lasting effect on astronomy up to the Renaissance. In his *Planetary Hypotheses* Ptolemy ventured into the realm of cosmology, developing a physical model of his geometric system, in a universe many times smaller than the more realistic conception of Aristarchus of Samos four centuries earlier.

India

Ancient Indian astrology is based upon sidereal calculation. The sidereal astronomy is based upon the stars and the sidereal period is the time that it takes the object to make one full orbit around the Sun, relative to the stars. It can be traced to the final centuries BC with the Vedanga Jyotisha attributed to Lagadha, one of the circum-Vedic texts, which describes rules for tracking the motions of the Sun and the Moon for the purposes of ritual. After formation of Indo-Greek kingdoms, Indian astronomy was influenced by Hellenistic astronomy (adopting the zodiacal signs or *rāśis*). Identical numerical computations for lunar cycles have been found to be used in India and in early Babylonian texts.[11]

Aryabhata (476–550), in his magnum opus *Aryabhatiya* (499), propounded a computational system based on a planetary model in which the Earth was taken to be spinning on its axis and the periods of the planets were given with respect to the Sun. He accurately calculated many astronomical constants, such as the periods of the planets, times of the solar and lunar eclipses, and the instantaneous motion of the Moon.[12] [13] Early followers of Aryabhata's model included Varahamihira, Brahmagupta, and Bhaskara II.

Astronomy was advanced during the Sunga Empire and many star catalogues were produced during this time. The Sunga period is known as the "Golden age of astronomy in India".

Brahmagupta (598-668) was the head of the astronomical observatory at Ujjain and during his tenure there wrote a text on astronomy, the *Brahmasphutasiddhanta* in 628. He was the earliest to use algebra to solve astronomical problems. He also developed methods for calculations of the motions and places of various planets, their rising and setting, conjunctions, and the calculation of eclipses.

Bhāskara II (1114–1185) was the head of the astronomical observatory at Ujjain, continuing the mathematical tradition of Brahmagupta. He wrote the *Siddhantasiromani* which consists of two parts: *Goladhyaya* (sphere) and *Grahaganita* (mathematics of the planets). He also calculated the time taken for the Earth to orbit the sun to 9 decimal places. The Buddhist University of Nalanda at the time offered formal courses in astronomical studies.

Other important astronomers from India include Madhava of Sangamagrama, Nilakantha Somayaji and Jyeshtadeva, who were members of the Kerala school of astronomy and mathematics from the 14th century to the 16th century. Nilakantha Somayaji, in his *Aryabhatiyabhasya*, a commentary on Aryabhata's *Aryabhatiya*, developed his own computational system for a partially heliocentric planetary model, in which Mercury, Venus, Mars, Jupiter and Saturn orbit the Sun, which in turn orbits the Earth, similar to the Tychonic system later proposed by Tycho Brahe in the late 16th century. Nilakantha's system, however, was mathematically more effient than the Tychonic system, due to correctly taking into account the equation of the centre and latitudinal motion of Mercury and Venus. Most astronomers of the Kerala school of astronomy and mathematics who followed him accepted his planetary model.[14] [15]

China

The astronomy of East Asia began in China. Solar term was completed in Warring States Period. The knowledge of Chinese astronomy was introduced into East Asia.

Astronomy in China has a long history. Detailed records of astronomical observations were kept from about the 6th century BC, until the introduction of Western astronomy and the telescope in the 17th century. Chinese astronomers were able to precisely predict comets and eclipses.

Much of early Chinese astronomy was for the purpose of timekeeping. The Chinese used a lunisolar calendar, but because the cycles of the Sun and the Moon are different, astronomers often prepared new calendars and made observations for that purpose.

Astrological divination was also an important part of astronomy. Astronomers took careful note of "guest stars" which suddenly appeared among the fixed stars. They were the first to record a supernova, in the Astrological Annals of the Houhanshu in 185 A.D. Also, the supernova that created the Crab Nebula in 1054 is an example of a "guest star" observed by Chinese astronomers, although it was not recorded by their European contemporaries. Ancient astronomical records of phenomena like supernovae and comets are sometimes used in modern astronomical studies.

The world's first star catalogue was made by Gan De, a Chinese astronomer, in 4th century BC.

Mesoamerica

Maya astronomical codices include detailed tables for calculating phases of the Moon, the recurrence of eclipses, and the appearance and disappearance of Venus as morning and evening star. The Maya based their calendrics in the carefully calculated cycles of the Pleiades, the Sun, the Moon, Venus, Jupiter, Saturn, Mars, and also they had a precise description of the eclipses as depicted in the Dresden Codex, as well as the ecliptic or zodiac, and the Milky Way was crucial in their Cosmology.[16] A number of important Maya structures are believed to have been oriented toward the extreme risings and settings of Venus. To the ancient Maya, Venus was the patron of war and many recorded battles are believed to have been timed to the motions of this planet. Mars is also mentioned in preserved astronomical codices and early mythology.[17]

Although the Maya calendar was not tied to the Sun, John Teeple has proposed that the Maya calculated the solar year to somewhat greater accuracy than the Gregorian calendar.[18] Both astronomy and an intricate numerological scheme for the measurement of time were vitally important components of Maya religion.

Islamic astronomy

The Arabic world under Islam had become highly cultured, and many important works of knowledge from Greek astronomy and Indian astronomy were translated into Arabic, used and stored in libraries throughout the area. An important contribution by Islamic astronomers was their emphasis on observational science and observational astronomy[19] This led to the emergence of the first astronomical observatories in the Muslim world by the early 9th century.[20] [21] Zij star catalogues were produced at these observatories.

The late 9th century Persian astronomer Ahmad ibn Muhammad ibn Kathīr al-Farghānī wrote extensively on the motion of celestial bodies. His work was translated into Latin during the Latin translations of the 12th century. In the 9th century, Ja'far ibn Muhammad Abu Ma'shar al-Balkhi (Albumasar) developed a planetary model which has been interpreted as a heliocentric model.[22] This is due to his orbital revolutions of the planets being given as heliocentric revolutions rather than geocentric revolutions, and the only known planetary theory in which this occurs is in the heliocentric theory. His work on planetary theory has not survived, but his astronomical data was later recorded by al-Hashimi and Biruni.[22]

In the 10th century, Abd al-Rahman al-Sufi (Azophi) carried out observations on the stars and described their positions, magnitudes, brightness, and colour and drawings for each constellation in his *Book of Fixed Stars*. He also gave the first descriptions and pictures of "A Little Cloud" now known as the Andromeda Galaxy. He mentions it as lying before the mouth of a Big Fish, an Arabic constellation. This "cloud" was apparently commonly known to the Isfahan astronomers, very probably before 905 AD.[23] The first recorded mention of the Large Magellanic Cloud was also given by al-Sufi.[24] [25] In 1006, Ali ibn Ridwan observed SN 1006, the brightest supernova in recorded history, and left a detailed description of the temporary star.

In the late 10th century, a huge observatory was built near Tehran, Iran, by the astronomer Abu-Mahmud al-Khujandi who observed a series of meridian transits of the Sun, which allowed him to calculate the obliquity of the ecliptic, also known as the tilt of the Earth's axis relative to the Sun. In 11th-century Persia, Omar Khayyám compiled many tables and performed a reformation of the calendar that was more accurate than the Julian and came close to the Gregorian.

In the early 11th century, Ibn al-Haytham (Alhazen) wrote the *Maqala fi daw al-qamar* (*On the Light of the Moon*) some time before 1021. This was the earliest attempt at applying the experimental method to astronomy and astrophysics, and thus the first successful at combining mathematical astronomy with "physics" (which then referred to natural philosophy) for several of his astronomical hypotheses. He disproved the universally held opinion that the moon reflects sunlight like a mirror and correctly concluded that it "emits light from those portions of its surface which the sun's light strikes." In order to prove that "light is emitted from every point of the moon's illuminated surface," he built an "ingenious experimental device." Ibn al-Haytham had "formulated a clear conception of the relationship between an ideal mathematical model and the complex of observable phenomena; in particular, he was the first to make a systematic use of the method of varying the experimental conditions in a constant and uniform manner, in an experiment showing that the intensity of the light-spot formed by the projection of the moonlight through two small apertures onto a screen diminishes constantly as one of the apertures is gradually blocked up."[26]

Other Muslim advances in astronomy included the collection and correction of previous astronomical data, resolving significant problems in the Ptolemaic model, the development of the universal latitude-independent astrolabe by Arzachel,[27] the invention of numerous other astronomical instruments, the beginning of astrophysics and celestial mechanics after Ja'far Muhammad ibn Mūsā ibn Shākir theorized that the heavenly bodies and celestial spheres were subject to the same physical laws as Earth,[28] the first elaborate experiments related to astronomical phenomena, the introduction of exacting empirical observations and experimental techniques,[29] and the introduction of empirical testing by Ibn al-Shatir, who produced the first model of lunar motion which matched physical observations.[30]

In the 12th century, Fakhr al-Din al-Razi criticized the idea of the Earth's centrality within the universe, and instead argued that there are more than "a thousand thousand worlds (*alfa alfi 'awalim*) beyond this world such that each one of those worlds be bigger and more massive than this world as well as having the like of what this world has."[31] The first empirical observational evidence of the Earth's rotation was given by Nasīr al-Dīn al-Tūsī in the 13th century and by Ali Qushji in the 15th century, followed by Al-Birjandi who developed an early hypothesis on "circular inertia" by the early 16th century.[32] Natural philosophy (particularly Aristotelian physics) was separated from astronomy by Ibn al-Haytham (Alhazen) in the 11th century, by Ibn al-Shatir in the 14th century,[33] and Qushji in the 15th century, leading to the development of an independent astronomical physics.[32]

It is known that the Copernican heliocentric model in Nicolaus Copernicus' *De revolutionibus* employed geometrical constructions that had been developed previously by the Maragheh school,[34] [35] and that his arguments for the Earth's rotation were similar to those of Nasīr al-Dīn al-Tūsī and Ali al-Qushji.[32] Some have referred to the achievements of the Maragha school as a "Maragha Revolution", "Maragha School Revolution", or "Scientific Revolution before the Renaissance".[36]

Medieval Western Europe

After the significant contributions of Greek scholars to the development of astronomy, it entered a relatively static era in Western Europe from the Roman era through the Twelfth century. This lack of progress has led some astronomers to assert that nothing happened in Western European astronomy during the Middle Ages.[37] Recent investigations, however, have revealed a more complex picture of the study and teaching of astronomy in the period from the Fourth to the Sixteenth centuries.[38]

Western Europe entered the Middle Ages with great difficulties that affected the continent's intellectual production. The advanced astronomical treatises of classical antiquity were written in Greek, and with the decline of knowledge of that language, only simplified summaries and practical texts were available for study. The most influential writers to pass on this ancient tradition in Latin were Macrobius, Pliny, Martianus Capella, and Calcidius.[39] In the Sixth Century Bishop Gregory of Tours noted that he had learned his astronomy from reading Martianus Capella, and went on to employ this rudimentary astronomy to describe a method by which monks could determine the time of prayer at night by watching the stars.[40]

In the Seventh Century the English monk Bede of Jarrow published an influential text, On the Reckoning of Time, providing churchmen with the practical astronomical knowledge needed to compute the proper date of Easter using a procedure called *computus*. This text remained an important element of the education of Clergy from the Seventh

Century until well after the rise of the Universities in the Twelfth Century.[41]

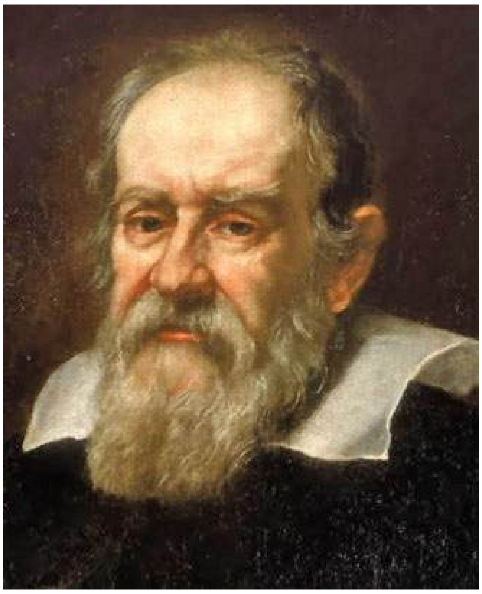
The range of surviving ancient Roman writings on astronomy and the teachings of Bede and his followers began to be studied in earnest during the revival of learning sponsored by the emperor Charlemagne.[42] By the Ninth Century rudimentary techniques for calculating the position of the planets were circulating in Western Europe; medieval scholars recognized their technical flaws, but texts describing these techniques continued to be copied, reflecting an interest in the motions of the planets and in their astrological significance.[43]

Building on this astronomical background, in the Tenth Century European scholars such as Gerbert of Aurillac began to travel to the Spain and Sicily to seek out learning which they had heard existed in the Arabic-speaking world. There they first encountered various practical astronomical techniques concerning the calendar and timekeeping, most notably those dealing with the astrolabe. Soon scholars such as Hermann of Reichenau were writing texts in Latin on the uses and construction of the astrolabe and others, such as Walcher of Malvern, were using the astrolabe to observe the time of eclipses in order to test the validity of computistical tables.[44]

By the Twelfth century, scholars were traveling to Spain and Sicily to seek out more advanced astronomical and astrological texts, which they translated into Latin from Arabic and Greek to further enrich the astronomical knowledge of Western Europe. The arrival of these new texts coincided with the rise of the universities in medieval Europe, in which they soon found a home.[45] Reflecting the introduction of astronomy into the universities, John of Sacrobosco wrote a series of influential introductory astronomy textbooks: the Sphere, a Computus, a text on the Quadrant, and another on Calculation.[46]

In the 14th century , Nicole Oresme, later bishop of Liseux, showed that neither the scriptural texts nor the physical arguments advanced against the movement of the Earth were demonstrative and adduced the argument of simplicity for the theory that the earth moves, and *not* the heavens. However, he concluded "everyone maintains, and I think myself, that the heavens do move and not the earth: For God hath established the world which shall not be moved."[47] In the 15th century, cardinal Nicholas of Cusa suggested in some of his scientific writings that the Earth revolved around the Sun, and that each star is itself a distant sun. He was not, however, describing a scientifically verifiable theory of the universe.

Renaissance Period



Galileo Galilei (1564–1642) crafted his own telescope and discovered that our Moon had craters, that Jupiter had moons, that the Sun had spots, and that Venus had phases like our Moon.

The renaissance came to astronomy with the work of Nicolaus Copernicus, who proposed a heliocentric system, in which the planets revolved around the Sun and not the Earth. His *De revolutionibus* provided a full mathematical discussion of his system, using the geometrical techniques that had been traditional in astronomy since before the time of Ptolemy. His work was later defended, expanded upon and modified by Galileo Galilei and Johannes Kepler.

Galileo was among the first to use a telescope to observe the sky and after constructing a 20x refractor telescope he discovered the four largest moons of Jupiter in 1610. This was the first observation of satellites orbiting another planet. He also found that our Moon had craters and observed (and correctly explained) sunspots. Galileo noted that Venus exhibited a full set of phases resembling lunar phases. Galileo argued that these observations supported the Copernican system and were, to some extent, incompatible with the favored model of the Earth at the center of the universe.[48]

Uniting physics and astronomy

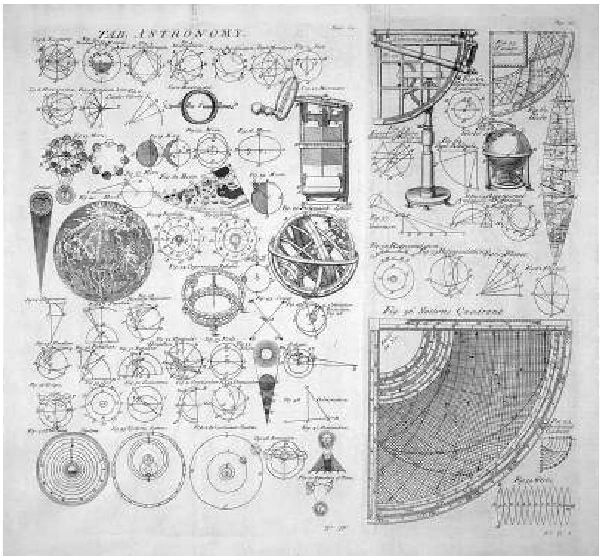


Plate with figures illustrating articles on astronomy, from the 1728 *Cyclopaedia*

Although the motions of celestial bodies had been qualitatively explained in physical terms since Aristotle introduced celestial movers in his Metaphysics and a fifth element in his On the Heavens, Johannes Kepler was the first to attempt to derive mathematical predictions of celestial motions from assumed physical causes.[49] [50] Combining his physical insights with the unprecedentedly accurate naked-eye observations made by Tycho Brahe,[51] [52] [53] Kepler discovered the three laws of planetary motion that now carry his name.[54]

Isaac Newton developed further ties between physics and astronomy through his law of universal gravitation. Realising that the same force that attracted objects to the surface of the Earth held the moon in orbit around the Earth, Newton was able to explain – in one theoretical framework – all known gravitational phenomena. In his Philosophiae Naturalis Principia Mathematica, he derived Kepler's laws from first principles. Newton's theoretical developments lay many of the foundations of modern physics.

Modern astronomy

At the end of the 19th century it was discovered that, when decomposing the light from the Sun, a multitude of spectral lines were observed (regions where there was less or no light). Experiments with hot gases showed that the same lines could be observed in the spectra of gases, specific lines corresponding to unique elements. It was proved that the chemical elements found in the Sun (chiefly hydrogen and helium) were also found on Earth. During the 20th century spectrometry (the study of these lines) advanced, especially because of the advent of quantum physics, that was necessary to understand the observations.

Although in previous centuries noted astronomers were exclusively male, at the turn of the 20th century women began to play a role in the great discoveries. In this period prior to modern computers, women at the United States Naval Observatory (USNO), Harvard University, and other astronomy research institutions began to be hired as human "computers," who performed the tedious calculations while scientists performed research requiring more background knowledge. [55] A number of discoveries in this period were originally noted by the women "computers" and reported to their supervisors. For example, at the Harvard Observatory Henrietta Swan Leavitt discovered the cepheid variable star period-luminosity relation which she further developed into the first method of measuring distance outside of our solar system. Annie Jump Cannon organized the stellar spectral types according to stellar temperature, and Maria Mitchell discovered a comet using a telescope. According to Lewis D. Eigen, Cannon alone, "in only 4 years discovered and catalogued more stars than all the men in history put together."[56] (See [57] for more women astronomers.) Most of these women received little or no recognition during their lives due to their lower professional standing in the field of astronomy. Although their discoveries and methods are taught in classrooms around the world, few students of astronomy can attribute the works to their authors or have any idea that there were active female astronomers at the end of the 19th century.

Cosmology and the expansion of the universe

Most of our current knowledge was gained during the 20th century. With the help of the use of photography, fainter objects were observed. Our sun was found to be part of a galaxy made up of more than 10^{10} stars (10 billion stars). The existence of other galaxies, one of the matters of *the great debate*, was settled by Edwin Hubble, who identified the Andromeda nebula as a different galaxy, and many others at large distances and receding, moving away from our galaxy.

Physical cosmology, a discipline that has a large intersection with astronomy, made huge advances during the 20th century, with the model of the hot big bang heavily supported by the evidence provided by astronomy and physics, such as the redshifts of very distant galaxies and radio sources, the cosmic microwave background radiation, Hubble's law and cosmological abundances of elements.

New windows into the Cosmos open

Late in the 19th century, scientists began discovering forms of light which were invisible to the naked eye: X-Rays, gamma rays, radio waves, microwaves, ultraviolet radiation, and infrared radiation. This had a major impact on astronomy, spawning the fields of infrared astronomy, radio astronomy, x-ray astronomy and finally gamma-ray astronomy. With the advent of spectroscopy it was proven that other stars were similar to our own sun, but with a range of temperatures, masses and sizes. The existence of our galaxy, the Milky Way, as a separate group of stars was only proven in the 20th century, along with the existence of "external" galaxies, and soon after, the expansion of the universe seen in the recession of most galaxies from us.

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- DIO: The International Journal of Scientific History (http://www.dioi.org)
- Journal for the History of Astronomy
- Journal of Astronomical History and Heritage (http://www.jcu.edu.au/school/mathphys/astronomy/jah2/index.shtml)

External links

- Astronomiae Historia / History of Astronomy (http://www.astro.uni-bonn.de/~pbrosche/) at the Astronomical Institutes of Bonn University.
- Commission 41 (History of Astronomy) (http://www.le.ac.uk/has/c41/) of the International Astronomical Union (IAU)
- Society for the History of Astronomy (http://www.shastro.org.uk)
- Mayan Astronomy (http://www.authenticmaya.com/maya_astronomy.htm)
- Caelum Antiquum (http://penelope.uchicago.edu/Thayer/E/Gazetteer/Topics/astronomy/home.html): Ancient Astronomy and Astrology at LacusCurtius

- The Antikythera Calculator (Italian and English versions) - Ing. Giovanni Pastore (http://www.giovannipastore.it/ANTIKYTHERA.htm)
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Archaeoastronomy

The rising Sun illuminates the inner chamber of Newgrange, Ireland, only at the winter solstice.

Archaeoastronomy (also spelled **archeoastronomy**) is the study of how people in the past "have understood the phenomena in the sky, how they used phenomena in the sky and what role the sky played in their cultures."[1] Clive Ruggles argues it is misleading to consider archaeoastronomy to be the study of ancient astronomy, as modern astronomy is a scientific discipline, while archaeoastronomy considers other cultures' symbolically rich cultural interpretations of phenomena in the sky.[2] [3] It is often twinned with **ethnoastronomy**, the anthropological study of skywatching in contemporary societies. Archaeoastronomy is also closely associated with historical astronomy, the use of historical records of heavenly events to answer astronomical problems and the history of astronomy, which uses written records to evaluate past astronomical practice.

Archaeoastronomy uses a variety of methods to uncover evidence of past practices including archaeology, anthropology, astronomy, statistics and probability, and history. Because these methods are diverse and use data from such different sources, the problem of integrating them into a coherent argument has been a long-term issue for archaeoastronomers.[4]

Archaeoastronomy fills complementary niches in landscape archaeology and cognitive archaeology. Material evidence and its connection to the sky can reveal how a wider landscape can be integrated into beliefs about the cycles of nature, such as Mayan astronomy and its relationship with agriculture.[5] Other examples which have brought together ideas of cognition and landscape include studies of the cosmic order embedded in the roads of settlements.[6] [7]

Archaeoastronomy can be applied to all cultures and all time periods. The meanings of the sky vary from culture to culture; nevertheless there are scientific methods which can be applied across cultures when examining ancient beliefs.[8] It is perhaps the need to balance the social and scientific aspects of archaeoastronomy which led Clive Ruggles to describe it as: *"...[A] field with academic work of high quality at one end but uncontrolled speculation bordering on lunacy at the other."*[9]

History of archaeoastronomy

> In his short history of 'Astro-archaeology' John Michell argued that the status of research into ancient astronomy had improved over the past two centuries, going 'from lunacy to heresy to interesting notion and finally to the gates of orthodoxy.' Nearly two decades later, we can still ask the question: Is archaeoastronomy still waiting at the gates of orthodoxy or has it gotten inside the gates?
>
> —Todd Bostwick quoting John Michell[10]

Two hundred years before Michell wrote the above, there were no archaeoastronomers and there were no professional archaeologists, but there were astronomers and antiquarians. Some of their works are considered precursors of archaeoastronomy; antiquarians interpreted the astronomical orientation of the ruins that dotted the English countryside as William Stukeley did of Stonehenge in 1740,[11] while John Aubrey in 1678[12] and Henry Chauncy in 1700 sought similar astronomical principles underlying the orientation of churches.[13] Late in the nineteenth century astronomers such as Richard Proctor and Charles Piazzi Smyth investigated the astronomical orientations of the pyramids.[14]

The term *archaeoastronomy* was first used by Elizabeth Chesley Baity (at the suggestion of Euan MacKie) in 1973,[15] but as a topic of study it may be much older, depending on how archaeoastronomy is defined. Clive Ruggles[16] says that Heinrich Nissen, working in the mid-nineteenth century was arguably the first archaeoastronomer. Rolf Sinclair[17] says that Norman Lockyer, working in the late 19th and early 20th centuries, could be called the 'father of archaeoastronomy.' Euan MacKie[18] would place the origin even later, stating: "...the genesis and modern flowering of archaeoastronomy must surely lie in the work of Alexander Thom in Britain between the 1930s and the 1970s.

Early archaeoastronomy surveyed Megalithic constructs in the British Isles, at sites like Auglish in County Londonderry, in an attempt to find statistical patterns

. In the 1960s the work of the engineer Alexander Thom and that of the astronomer Gerald Hawkins, who proposed that Stonehenge was a Neolithic computer,[19] inspired new interest in the astronomical features of ancient sites. The claims of Hawkins were largely dismissed,[20] but this was not the case for Alexander Thom's work, whose survey results of megalithic sites hypothesized widespread practice of accurate astronomy in the British Isles.[21] Euan MacKie, recognizing that Thom's theories needed to be tested, excavated at the Kintraw standing stone site in Argyllshire in 1970 and 1971 to check whether the latter's prediction of an observation platform on the hill slope above the stone was correct. There was an artificial platform there and this apparent verification of Thom's long alignment hypothesis (Kintraw was diagnosed as an accurate winter solstice site) led him to check Thom's geometrical theories at the Cultoon stone circle in Islay, also with a positive result. MacKie therefore broadly accepted Thom's conclusions and published new prehistories of Britain.[22] In contrast a re-evaluation of Thom's fieldwork by Clive Ruggles argued that Thom's claims of high accuracy astronomy were not fully supported by the evidence.[23] Nevertheless Thom's legacy remains strong, Krupp[24] wrote in 1979, "Almost singlehandedly he has established the standards for archaeo-astronomical fieldwork and interpretation, and his amazing results have stirred controversy during the last three decades." His influence endures and practice of statistical testing of data remains one of the methods of archaeoastronomy.[25] [26]

The approach in the New World, where anthropologists began to consider more fully the role of astronomy in Amerindian civilizations, was markedly different. They had access to sources that the prehistory of Europe lacks such as ethnographies[27] [28] and the historical records of the early colonizers. Following the pioneering example of Anthony Aveni,[29] [30] this allowed New World archaeoastronomers to make claims for motives which in the Old World would have been mere speculation. The concentration on historical data led to some claims of high accuracy that were comparatively weak when compared to the statistically led investigations in Europe.[31]

It has been proposed that Maya sites such as Uxmal were built in accordance with astronomical alignments.

This came to a head at a meeting sponsored by the IAU in Oxford in 1981.[32] The methodologies and research questions of the participants were considered so different that the conference proceedings were published as two volumes.[33] [34] Nevertheless the conference was considered a success in bringing researchers together and Oxford conferences have continued every four or five years at locations around the world. The subsequent conferences have resulted in a move to more interdisciplinary approaches with researchers aiming to combine the contextuality of archaeological research,[35] which broadly describes the state of archaeoastronomy today, rather than merely establishing the existence of ancient astronomies archaeoastronomers seek to explain why people would have an interest in the night sky.

Archaeoastronomy and its relations to other disciplines

> ...[O]ne of the most endearing characteristics of archaeoastronomy is its capacity to set academics in different disciplines at loggerheads with each other.
>
> —Clive Ruggles[36]

Archaeoastronomy has long been seen as an interdisciplinary field that uses written and unwritten evidence to study the astronomies of other cultures. As such, it can be seen as connecting other disciplinary approaches for investigating ancient astronomy: astroarchaeology (an obsolete term for studies that draw astronomical information from the alignments of ancient architecture and landscapes), history of astronomy (which deals primarily with the written textual evidence), and ethnoastronomy (which draws on the ethnohistorical record and contemporary ethnographic studies).[37] [38]

Reflecting Archaeoastronomy's development as an interdisciplinary subject, research in the field is conducted by investigators trained in a wide range of disciplines. Authors of recent doctoral dissertations have described their work as concerned with the fields of archaeology and cultural anthropology; with various fields of history including the history of specific regions and periods, the history of science and the history of religion; and with the relation of astronomy to art, literature and religion. Only rarely did they describe their work as astronomical, and then only as a secondary category.[39]

Both practicing archaeoastronomers and observers of the discipline approach it from different perspectives. George Gummerman and Miranda Warburton view archaeoastronomy as part of an archaeology informed by cultural anthropology and aimed at understanding a "group's conception of themselves in relation to the heavens', in a word, its cosmology.[40] Todd Bostwick argued that "archaeoastronomy is anthropology – the study of human behavior in the past and present."[41] Paul Bahn has described archaeoastronomy as an area of cognitive archaeology.[42] Other researchers relate archaeoastronomy to the history of science, either as it relates to a culture's observations of nature and the conceptual framework they devised to impose an order on those observations[43] or as it relates to the political motives which drove particular historical actors to deploy certain astronomical concepts or techniques.[44] [45] Art historian Richard Poss took a more flexible approach, maintaining that the astronomical rock art of the North American Southwest should be read employing "the hermeneutic traditions of western art history and art criticism"[46] Astronomers, however, raise different questions, seeking to provide their students with identifiable precursors of their discipline, and are especially concerned with the important question of how to confirm that specific sites are, indeed, intentionally astronomical.[47]

The reactions of professional archaeologists to archaeoastronomy have been decidedly mixed. Some expressed incomprehension or even hostility, varying from a rejection by the archaeological mainstream of what they saw as an archaeoastronomical fringe to an incomprehension between the cultural focus of archaeologists and the quantitative focus of early archaeoastronomers.[48] Yet archaeologists have increasingly come to incorporate many of the insights from archaeoastronomy into archaeology textbooks[49] and, as mentioned above, some students wrote archaeology dissertations on archaeoastronomical topics.

Since archaeoastronomers disagree so widely on the characterization of the discipline, they even dispute its name. All three major international scholarly associations relate archaeoastronomy to the study of culture, using the term *Astronomy in Culture* or a translation. Michael Hoskin sees an important part of the discipline as fact-collecting, rather than theorizing, and proposed to label this aspect of the discipline *Archaeotopography*.[50] Ruggles and Saunders proposed *Cultural Astronomy* as a unifying term for the various methods of studying folk astronomies.[51] Others have argued that astronomy is an inaccurate term, what are being studied are cosmologies and people who object to the use of logos have suggested adopting the Spanish *cosmovisión*.[52]

When debates polarise between techniques, the methods are often referred to by a colour code, based on the colours of the bindings of the two volumes from the first Oxford Conference, where the approaches were first distinguished.[53] Green (Old World) archaeoastronomers rely heavily on statistics and are sometimes accused of missing the cultural context of what is a social practice. Brown (New World) archaeoastronomers in contrast have abundant ethnographic and historical evidence and have been described as 'cavalier' on matters of measurement and statistical analysis.[54] Finding a way to integrate various approaches has been a subject of much discussion since the early 1990s.[55] [56]

Methodology

> For a long time I have believed that such diversity requires the invention of some all-embracing theory. I think I was very naïve in thinking that such a thing was ever possible.
>
> —Stanislaw Iwaniszewski[57]

There is no one way to do Archaeoastronomy. The divisions between archaeoastronomers tend not to be between the physical scientists and the social scientists. Instead it tends to depend on the location of kind of data available to the researcher. In the Old World, there is little data but the sites themselves; in the New World, the sites were supplemented by ethnographic and historic data. The effects of the isolated development of archaeoastronomy in different places can still often be seen in research today. Research methods can be classified as falling into one of two approaches, though more recent projects often use techniques from both categories.

Green archaeoastronomy

Green Archaeoastronomy is named after the cover of the book *Archaeoastronomy in the Old World*.[58] It is based primarily on statistics and is particularly apt for prehistoric sites where the social evidence is relatively scant compared to the historic period. The basic methods were developed by Alexander Thom during his extensive surveys of British megalithic sites.

Thom wished to examine whether or not prehistoric peoples used high-accuracy astronomy. He believed that by using horizon astronomy, observers could make estimates of dates in the year to a specific day. The observation required finding a place where on a specific date the sun set into a notch on the horizon. A common theme is a mountain which blocked the Sun, but on the right day would allow the tiniest fraction to re-emerge on the other side for a 'double sunset'. The animation below shows two sunsets at a hypothetical site, one the day before the summer solstice and one at the summer solstice, which has a double sunset. Horizon astronomy is arguably inaccurate, due to variations in refraction.

To test this idea he surveyed hundreds of stone rows and circles. Any individual alignment could indicate a direction by chance, but he planned to show that together the distribution of alignments was non-random, showing that there was an astronomical intent to the orientation of at least some of the alignments. His results indicated the existence of eight, sixteen, or perhaps even thirty-two approximately equal divisions of the year. The two solstices, the two equinoxes and four cross-quarter days, days half-way between a solstice and the equinox were associated with the medieval Celtic calendar.[59] While not all these conclusions have been accepted, it has had an enduring influence on archaeoastronomy, especially in Europe.

Euan MacKie has supported Thom's analysis, to which he added an archaeological context by comparing Neolithic Britain to the Mayan civilization to argue for a stratified society in this period.[22] To test his ideas he conducted a couple of excavations at proposed prehistoric observatories in Scotland. Kintraw is a site notable for its four-meter high standing stone. Thom proposed that this was a foresight to a point on the distant horizon between Beinn Shianaidh and Beinn o'Chaolias on Jura.[60] This, Thom argued, was a notch on the horizon where a double sunset would occur at midwinter. However, from ground level, this sunset would be obscured by a ridge in the landscape, and the viewer would need to be raised by two meters: another observation platform was needed. This was identified across a gorge where a platform was formed from small stones. The lack of artifacts caused concern for some archaeologists and the petrofabric analysis was inconclusive, but further research at Maes Howe[61] and on the Bush Barrow Lozenge[62] led MacKie to conclude that while the term 'science' may be anachronistic, Thom was broadly correct upon the subject of high-accuracy alignments.[63]

In contrast Clive Ruggles has argued that there are problems with the selection of data in Thom's surveys. meaning that the arguments for high accuracy astronomy are unproven.[64] [65] A deeper criticism of Green archaeoastronomy is that while it can answer *whether* there was likely to be an interest in astronomy in past times, its lack of a social element means that it struggles to answer *why* people would be interested, which makes it of limited use to people asking questions about the society of the past. Keith Kintigh wrote: "To put it bluntly, in many cases it doesn't matter much to the progress of anthropology whether a particular archaeoastronomical claim is right or wrong because the information doesn’t inform the current interpretive questions."[66] Nonetheless the study of alignments remains a staple of archaeoastronomical research, especially in Europe.[67]

Brown archaeoastronomy

In contrast to the largely alignment-orientated statistically-led methods of Green archaeoastronomy, Brown archaeoastronomy has been identified as being closer to the history of astronomy or to cultural history, insofar as it draws on historical and ethnographic records to enrich its understanding of early astronomies and their relations to calendars and ritual.[53] The many records of native customs and beliefs made by the Spanish chroniclers means that Brown archaeoastronomy is most often associated with studies of astronomy in the Americas.[68]

One famous site where historical records have been used to interpret sites is Chichen Itza. Rather than analysing the site and seeing which targets appear popular, archaeoastronomers have instead examined the ethnographic records to see what features of the sky were important to the Mayans and then sought archaeological correlates. One example which could have been overlooked without historical records is the Mayan interest in the planet Venus. This interest is attested to by the Dresden codex which contains tables with information about the Venus's appearances in the sky.[69] These cycles would have been of astrological and ritual significance as Venus was associated with Quetzalcoatl or Xolotl.[70] Associations of architectural features with settings of Venus can be found in Chichen Itza.

"El Caracol" a possible observatory temple at Chichen Itza.

The Temple of the Warriors bears iconography depicting feathered serpents associated with Quetzalcoatl or Kukulcan. This means that the building's alignment towards the place on the horizon where Venus first appears in the evening sky (when it coincides with the rainy season) may be meaningful.[71] Aveni claims that another building associated with the planet Venus in the form of Kukulcan, and the rainy season at Chichen Itza is the Caracol.[72] This is a building with circular tower and doors facing the cardinal directions. The base faces the most northerly setting of Venus. Additionally the pillars of a stylobate on the building's upper platform were painted black and red. These are colours associated with Venus as an evening and morning star.[73] However the windows in the tower seem to have been little more than slots, making them poor at letting light in, but providing a suitable place to view out.[74]

Aveni states that one of the strengths of the Brown methodology is that it can explore astronomies invisible to statistical analysis and offers the astronomy of the Incas as another example. The empire of the Incas was conceptually divided using *ceques* radial routes emanating from the capital at Cusco. Thus there are alignments in all directions which would suggest there is little of astronomical significance, However, ethnohistorical records show that the various directions do have cosmological and astronomical significance with various points in the landscape being significant at different times of the year.[75] [76] In eastern Asia archaeoastronomy has developed from the History of Astronomy and much archaeoastronomy is searching for material correlates of the historical record. This is due to the rich historical record of astronomical phenomena which, in China, stretches back into the Han dynasty, in the second century BC.[77]

A criticism of this method is that it can be statistically weak. Schaefer in particular has questioned the how robust the claimed alignments in the Caracol are.[78] [79] Because of the wide variety of evidence, which can include artefacts as well as sites, there is no one way to practice archaeoastronomy.[80] Despite this it is accepted that archaeoastronomy is not a discipline that sits in isolation. Because archaeoastronomy is an interdisciplinary field, whatever is being investigated should make sense both archaeologically and astronomically. Studies are more likely to be considered sound if they use theoretical tools found in archaeology like analogy and homology and if they can demonstrate an understanding of accuracy and precision found in astronomy.

Source materials

Because archaeoastronomy is about the many and various ways people interacted with the sky, there are a diverse range of sources giving information about astronomical practices.

Alignments

A common source of data for archaeoastronomy is the study of alignments. This is based on the assumption that the axis of alignment of an archaeological site is meaningfully orientated towards an astronomical target. Brown archaeoastronomers may justify this assumption through reading historical or ethnographic sources, while Green archaeoastronomers tend to prove that alignments are unlikely to be selected by chance, usually by demonstrating common patterns of alignment at multiple sites.

An alignment is calculated by measuring the azimuth, the angle from north, of the structure and the altitude of the horizon it faces[81] The azimuth is usually measured using a theodolite or a compass. A compass is easier to use, though the deviation of the Earth's magnetic field from true north, known as its magnetic declination must be taken into account. Compasses are also unreliable in areas prone to magnetic interference, such as sites being supported by scaffolding. Additionally a compass can only measure the azimuth to a precision of a half a degree.[82]

A theodolite can be considerably more accurate if used correctly, but it is also considerably more difficult to use correctly. There is no inherent way to align a theodolite with North and so the scale has to be calibrated using astronomical observation, usually the position of the Sun.[83] Because the position of celestial bodies changes with the time of day due to the Earth's rotation, the time of these calibration observations must be accurately known, or else there will be a systematic error in the measurements. Horizon altitudes can be measured with a theodolite or a clinometer.

Artifacts


The Antikythera mechanism (main fragment)

For artifacts such as the Sky Disc of Nebra, alleged to be a Bronze Age artefact depicting the cosmos,[84] [85] the analysis would be similar to typical post-excavation analysis as used in other sub-disciplines in archaeology. An artefact is examined and attempts are made to draw analogies with historical or ethnographical records of other peoples. The more parallels that can be found, the more likely an explanation is to be accepted by other archaeologists.

A more mundane example is the presence of astrological symbols found on some shoes and sandals from the Roman Empire. The use of shoes and sandals is well known, but Carol van Driel-Murray has proposed that astrological symbols etched onto sandals gave the footwear spiritual or medicinal meanings.[86] This is supported through citation of other known uses of astrological symbols and their connection to medical practice and with the historical records of the time.

Another well-known artefact with an astronomical use is the Antikythera mechanism. In this case analysis of the artefact, and reference to the description of similar devices described by Cicero, would indicate a plausible use for the device. The argument is bolstered by the presence of symbols on the mechanism, allowing the disc to be read.[87]

Art and inscriptions

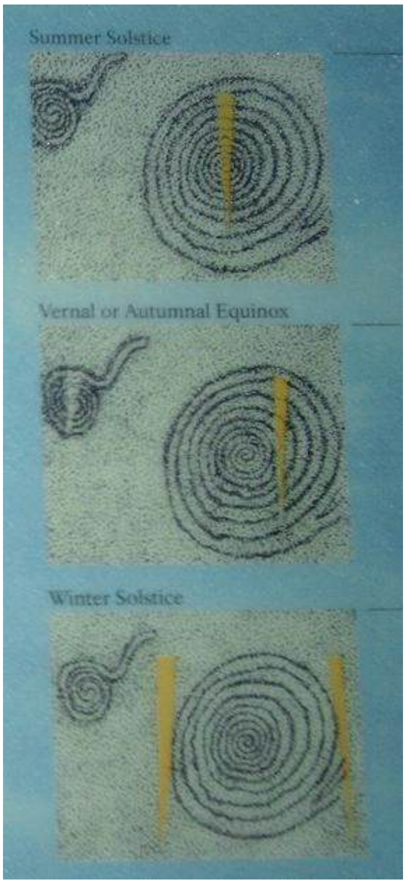


Diagram showing the location of the sun daggers on the Fajada Butte petroglyph on various days

Art and inscriptions may not be confined to artefacts, but also appear painted or inscribed on an archaeological site. Sometimes inscriptions are helpful enough to give instructions to a site's use. For example a Greek inscription on a stele (from Itanos) has been translated as:"Patron set this up for Zeus Epopsios. Winter solstice. Should anyone wish to know: off ‘the little pig’ and the stele the sun turns."[88] From Mesoamerica come Mayan and Aztec codices. These are folding books made from Amatl, processed tree bark on which are glyphs in Mayan or Aztec script. The Dresden codex contains information regarding the Venus cycle, confirming its importance to the Mayans.[69]

More problematic are those cases where the movement of the Sun at different times and seasons causes light and shadow interactions with petroglyphs. A widely known example is the Sun Dagger of Fajada Butte at which a glint of sunlight passes over a spiral petroglyph.[89] The location of the dagger on the petroglyph varies throughout the year. At the solstices a dagger can be seen either through the heart of the spiral or to either side of it. It is proposed that this petroglyph was created to mark these events. Recent studies have identified many similar sites in the US Southwest and Northwestern Mexico.[90] [91] It has been argued that the number of solstitial markers at these sites provides statistical evidence that they were intended to mark the solstices.[92] If no ethnographic nor historical data are found which can support this assertion then acceptance of the idea relies upon whether or not there are enough petroglyph sites in North America that such a correlation could occur by chance. It is helpful when petroglyphs are associated with existing peoples. This allows ethnoastronomers to question informants as to the meaning of such symbols.

Ethnographies

As well as the materials left by peoples themselves, there are also the reports of other who have encountered them. The historical records of the Conquistadores are a rich source of information about the precolumbian Americans. Ethnographers also provide material about many other peoples.

Aveni uses the importance of zenith passages as an example of the importance of ethnography. For peoples living between the tropics of Cancer and Capricorn there are two days of the year when the noon Sun passes directly overhead and casts no shadow. In parts of Mesoamerica this was considered a significant day as it would herald the arrival of rains, and so play a part in the cycle of agriculture. This knowledge is still considered important amongst Mayan Indians living in Central America today. The ethnographic records suggested to archaeoastronomers that this day may have been important to the ancient Mayans. Alignments to the sunrise and sunset on the day of the zenith passage have been found in Mayan cities such as Chichen Itza. There are also shafts known as 'zenith tubes' which illuminate subterranean rooms when the sun passes overhead found at places like Monte Alban and Xochicalco. It is only through the ethnography that we can speculate that the timing of the illumination was considered important in Mayan society.[93]

Ethnographies also caution against over-interpretation of sites. At Pueblo Bonito, in Chaco Canyon can be found a petroglyph with a star, crescent and hand. It has been argued that this is a record of the 1054 Supernova.[94] However anthropological evidence suggests this is not the case. The Zuni who live in the region mark sun-watching stations with a crescent, star, hand and sundisc, which can also be found at the site.[95] The local peoples appear to have adopted the supernova explanation *after* it was suggested by visitors to the site.[96]


An alleged 'supernova petroglyph' at Pueblo Bonito

Ethnoastronomy is also an important field outside of the Americas. For example anthropological work with Aboriginal Australians is producing much information about their Indigenous astronomies[97] and about their interaction with the modern world.[98]

Recreating the ancient sky

> ...[A]lthough different ways to do science and different scientific results do arise in different cultures, this provides little support for those who would use such differences to question the sciences' ability to provide reliable statements about the world in which we live.
>
> —Stephen McCluskey[99]

Once the researcher has data to test, it is often necessary to attempt to recreate ancient sky conditions to place the data in its historical environment.

Declination

To calculate what astronomical features a structure faced a coordinate system is needed. The stars provide such a system. If you were to go outside on a clear night you would observe the stars spinning around the celestial pole. This point is +90° if you are watching the North Celestial Pole or −90° if you are observing the Southern Celestial Pole.[100] The concentric circles the stars trace out are lines of celestial latitude, known as *declination*. The arc connecting the points on the horizon due East and due West (if the horizon is flat) and all points midway between the Celestial Poles is the Celestial Equator which has a declination of 0°. The visible declinations vary depending where you are on the globe. Only an observer on the North Pole of Earth would be unable to see any stars from the Southern Celestial Hemisphere at night (see diagram below). Once a declination has been found for the point on the horizon that a building faces it is then possible to say whether a specific body can be seen in that direction.

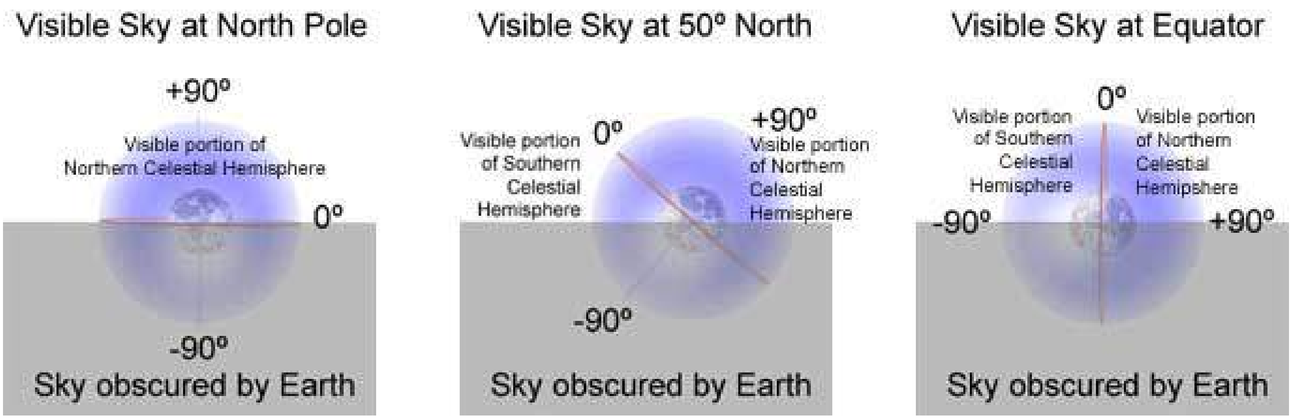


Diagram of the visible portions of sky at varying latitudes.

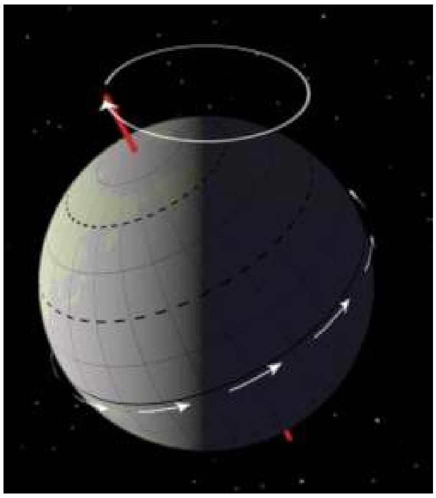
Solar positioning

While the stars are fixed to their declinations the Sun is not. The rising point of the Sun varies throughout the year. It swings between two limits marked by the solstices a bit like a pendulum, slowing as it reaches the extremes, but passing rapidly through the mid-point. If an archaeoastronomer can calculate from the azimuth and horizon height that a site was built to view a declination of +23.5° then he or she need not wait until 21 June to confirm the site does indeed face the summer solstice.[101] For more information see History of solar observation.

Lunar positioning

The Moon's appearance is considerably more complex. Its motion, like the Sun, is between two limits — known as *luna*stices rather than *sol*stices. However, its travel between lunastices is considerably faster. It takes a sidereal month to complete its cycle rather than the year long trek of the Sun. This is further complicated as the lunastices marking the limits of the Moon's movement move on an 18.6 year cycle. For slightly over nine years the extreme limits of the moon are outside the range of sunrise. For the remaining half of the cycle the Moon never exceeds the limits of the range of sunrise. However, much lunar observation was concerned with the *phase* of the Moon. The cycle from one New Moon to the next runs on an entirely different cycle, the Synodic month.[102] Thus when examining sites for lunar significance the data can appear sparse due the extremely variable nature of the moon. See Moon for more details.

Stellar positioning


Precessional movement.

Finally there is often a need to correct for the apparent movement of the stars. On the timescale of human civilisation the stars have maintained the same position relative to each other. Each night they appear to rotate around the celestial poles due to the Earth's rotation about its axis. However, the Earth spins rather like a spinning top. Not only does the Earth rotate, it wobbles. The Earth's axis takes around 25,800 years to complete one full wobble.[103] The effect to the archaeoastronomer is that stars did not rise over the horizon in the past in the same places as they do today. Nor did the stars rotate around Polaris as they do now. In the case of the Egyptian pyramids, it has been shown they were aligned towards Thuban, a faint star in the constellation of Draco.[104] The effect can be substanstial over relatively short lengths of time, historically speaking. For instance a person born on 25 December in Roman times would have been born with the sun in the constellation Capricorn. In the modern period a person born on the same date would have the sun in Sagittarius due to the precession of the equinoxes.

Transient phenomena

Halley's Comet depicted on the Bayeux tapestry

Additionally there are often transient phenomena, events which do not happen on an annual cycle. Most predictable are events like eclipses. In the case of solar eclipses these can be used to date events in the past. A solar eclipse mentioned by Herodotus enables us to date a battle between the Medes and the Lydians, which following the eclipse failed to happen, to 28 May, 585 BC.[105] Other easily calculated events are supernovae whose remains are visible to astronomers and therefore their positions and magnitude can be accurately calculated.

Some comets are predictable, most famously Halley's Comet. Yet as a class of object they remain unpredictable and can appear at any time. Some have extremely lengthy orbital periods which means their past appearances and returns cannot be predicted. Others may have only ever passed through the Solar System once and so are inherently unpredictable.[106]

Meteor showers should be predictable, but some meteors are cometary debris and so require calculations of orbits which are currently impossible to complete.[107] Other events noted by ancients include aurorae, sun dogs and rainbows all of which are as impossible to predict as the ancient weather, but nevertheless may have been considered important phenomena.

Major topics of archaeoastronomical research

> What has astronomy brought into the lives of cultural groups throughout history? The answers are many and varied...
>
> —Von Del Chamberlain and M. Jane Young[108]

The use of calendars

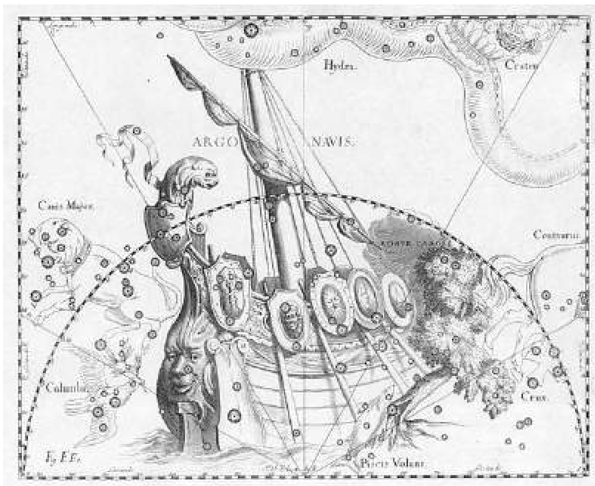
A common justification for the need for astronomy is the need to develop an accurate calendar for agricultural reasons. Ancient texts like Hesiod's Works and Days, an ancient farming manual, would appear to contradict this. Instead astronomical observations are used in combination with ecological signs, such as bird migrations to determine the seasons. Ethnoastronomical work with the Mursi of Ethiopia shows that haphazard astronomy continued until recent times in some parts of the world.[109] All the same, calendars appear to be an almost universal phenomenon in societies as they provide tools for the regulation of communal activities.

An example of a non-agricultural calendar is the *Tzolk'in* calendar of the Maya civilization of pre-Columbian Mesoamerica, which is a cycle of 260 days. This count is based on an earlier calendar and is found throughout Mesoamerica. This formed part of a more comprehensive system of Maya calendars which combined a series of astronomical observations and ritual cycles.[110]

Other peculiar calendars include ancient Greek calendars. These were nominally lunar, starting with the New Moon. In reality the calendar could pause or skip days with confused citizens inscribing dates by both the civic calendar and *ton theoi*, by the moon.[111] The lack of any universal calendar for ancient Greece suggests that coordination of panhellenic events such as games or rituals could be difficult and that astronomical symbolism may have been used as a politically neutral form of timekeeping.[112]

Myth and cosmology

Another motive for studying the sky is to understand and explain the universe. In these cultures myth was a tool for achieving this and the explanations, while not reflecting the standards of modern science, are cosmologies.



The constellation Argo Navis drawn by Johannes Hevelius in 1690.

The Incas arranged their empire to demonstrate their cosmology. The capital, Cusco, was at the centre of the empire and connected to it by means of ceques, conceptually straight lines radiating out from the centre.[113] These ceques connected the centre of the empire to the four *suyus*, which were regions defined by their direction from Cusco. The notion of a quartered cosmos is common across the Andes. Gary Urton, who has conducted fieldwork in the Andean villagers of Misminay, has connected this quartering with the appearance of the Milky Way in the night sky.[114] In one season it will bisect the sky and in another bisect it in a perpendicular fashion.

The importance of observing cosmological factors is also seen on the other side of the world. The Forbidden City in Beijing is laid out to follow cosmic order though rather than observing four directions the Chinese saw five, North, South, East, West and Centre. The Forbidden City occupied the centre of ancient Beijing.[115] One approaches the Emperor from the south, thus placing him in front of the circumpolar stars. This creates the situation of the heavens revolving around the person of the Emperor. The Chinese cosmology is now better known through its export as Feng

Shui.

There is also much information about how the universe was thought to work stored in the mythology of the constellations. The Barasana of the Amazon plan part of their annual cycle based on observation of the stars. When their constellation of the Caterpillar-Jaguar (roughly equivalent to the modern Scorpius) falls they prepare to catch the pupating caterpillars of the forest as they fall from the trees.[116] The caterpillars provide food at a season when other foods are scarce.[117]

A more well-known source of constellation myth are the texts of the Greeks and Romans. The origin of their constellations remains a matter of vigorous and occasionally fractious debate.[118] [119]

Displays of power

The Precinct of Amun-Re was aligned on the midwinter solstice.

By including celestial motifs in clothing it becomes possible for the wearer to make claims the power on Earth is drawn from above. It has been said that the Shield of Achilles described by Homer is also a catalogue of constellations.[120] In North America shields depicted in Comanche petroglyphs appear to include Venus symbolism.[121]

Solsticial alignments also can be seen as displays of power. When viewed from a ceremonial plaza on the Island of the Sun (the mythical origin place of the Sun) in Lake Titicaca, the Sun was seen to rise at the June solstice between two towers on a nearby ridge. The sacred part of the island was separated from the remainder of it by a stone wall and ethnographic records indicate that access to the sacred space was restricted to members of the Inca ruling elite. Ordinary pilgrims stood on a platform outside the ceremonial area to see the solstice Sun rise between the towers.[122]

In Egypt the temple of Amun-Re at Karnak has been the subject of much study. Evaluation of the site, taking into account the change over time of the obliquity of the ecliptic show that the Great Temple was aligned on the rising of the midwinter sun.[123] The length of the corridor down which sunlight would travel would have limited illumination at other times of the year.

In a later period the Serapeum in Alexandria was also said to have contained a solar alignment so that, on a specific sunrise, a shaft of light would pass across the lips of the statue of Serapis thus symbolising the Sun saluting the god.[124]

Major sites of archaeoastronomical interest

> At Stonehenge in England and at Carnac in France, in Egypt and Yucatán, across the whole face of the earth, are found mysterious ruins of ancient monuments, monuments with astronomical significance... They mark the same kind of commitment that transported us to the moon and our spacecraft to the surface of Mars.
>
> —Edwin Krupp[125]

Newgrange

Newgrange is a passage tomb in the Republic of Ireland dating from around 3,300 to 2,900 BC[126] For a few days around the Winter Solstice light shines along the central passageway into the heart of the tomb. What makes this notable is not that light shines in the passageway, but that it does not do so through the main entrance. Instead it enters via a hollow box above the main doorway discovered by Michael O'Kelly.[127] It is this roofbox which strongly indicates that the tomb was built with an astronomical aspect in mind. Clive Ruggles notes:


The sunlight enters the tomb at Newgrange via the roofbox built above the door.

> ...[F]ew people - archaeologists or astronomers- have doubted that a powerful astronomical symbolism was deliberately incorporated into the monument, demonstrating that a connection between astronomy and funerary ritual, at the very least, merits further investigation.[100]

The Pyramids of Giza

Since the first modern measurements of the precise cardinal orientations of the pyramids by Flinders Petrie, various astronomical methods have been proposed for the original establishment of these orientations.[128][129] It was recently proposed that this was done by observing the positions of two stars in the Plough / Big Dipper which was known to Egyptians as the thigh. It is thought that a vertical alignment between these two stars checked with a plumb bob was used to ascertain where North lay. The deviations from true North using this model reflect the accepted dates of construction.[130]


The pyramids of Giza.

Some have argued that the pyramids were laid out as a map of the three stars in the belt of Orion,[131] although this theory has been criticized by reputable astronomers.[132] [133]

El Castillo


Plumed Serpent

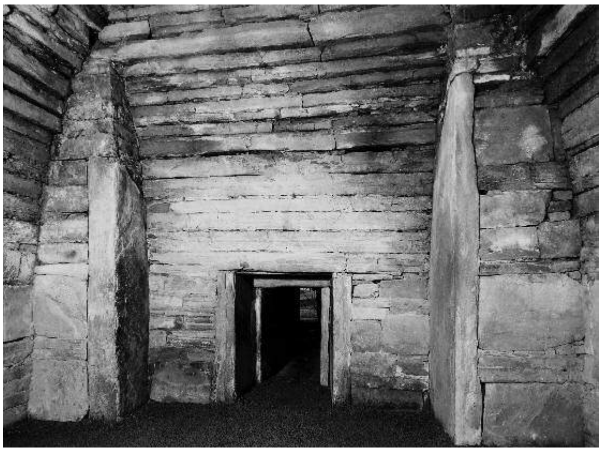
El Castillo, also known as Kukulcán's Pyramid, is a Mesoamerican step-pyramid built in the centre of Mayan center of Chichen Itza in Mexico. Several architectural features have suggested astronomical elements. Each of the stairways built into the sides of the pyramid has 91 steps. Along with the extra one for the platform at the top, this totals 365 steps, which is possibly one for each day of the year (365.25) or the number of lunar orbits in 10,000 rotations (365.01). A visually striking effect is seen every March and September as an unusual shadow occurs on the equinoxes. A shadow appears to descend the west balustrade of the northern stairway. The visual effect is of a serpent descending the stairway, with its head at the base in light. Additionally the western face points to sunset around 25 May, traditionally the date of transition from the dry to the rainy season[134]

Stonehenge


The sun rising over Stonehenge at the 2005 Summer Solstice.

Many astronomical alignments have been claimed for Stonehenge, a complex of megaliths and earthworks in the Salisbury Plain of England. The most famous of these is the midsummer alignment, where the Sun rises over the Heel Stone. However, this interpretation has been challenged by some archaeologists who argue that the midwinter alignment, where the viewer is outside Stonehenge and sees the sun setting in the henge, is the more significant alignment, and the midsummer alignment may be a coincidence due to local topography.[135] As well as solar alignments, there are proposed lunar alignments. The four station stones mark out a rectangle. The short sides point towards the midsummer sunrise and midwinter sunset. The long sides if viewed towards the south-east, face the most southerly rising of the moon. Aveni notes these have never gained the acceptance which the claims solar alignments have.[136] Jacobs[137] noted the Heel Stone azimuth is one-seventh of circumference, matching the latitude of Avebury, while summer solstice sunrise azimuth is no longer equal to the construction era direction.

Maeshowe



The interior of Maeshowe chambered tomb.

This is an architecturally outstanding Neolithic chambered tomb on the Mainland of Orkney – probably dating to the early 3rd millennium BC, and where the setting sun at midwinter shines down the entrance passage into the central chamber (see Newgrange). In the 1990s further investigations were carried out to discover whether this was an accurate or an approximate solar alignment. Several new aspects of the site were discovered. In the first place the entrance passage faces the hills of the island Hoy, about 10 miles away. Secondly, it consists of two straight lengths, angled at a few degrees to each other. Thirdly, the outer part is aligned towards the midwinter sunset position on a level horizon just to the left of Ward Hill on Hoy. Fourthly the inner part points directly at the Barnhouse standing stone about 400m away and then to the right end of the summit of Ward Hill, just before it dips down to the notch between it at Cuilags to the right. This indicated line points to sunset on the first Sixteenths of the solar year (according to A. Thom) before and after the winter solstice and the notch at the base of the right slope of the Hill is at the same declination. Fourthly a similar 'double sunset' phenomenon is seen at the right end of Cuilags, also on Hoy; here the date is the first Eighth of the year before and after the winter solstice, at the beginning of November and February respectively – the Old Celtic festivals of Samhain and Imbolc. This alignment is not indicated by an artificial structure but gains plausibility from the other two indicated lines. Maeshowe is thus an extremely sophisticated calendar site which must have been positioned carefully in order to use the horizon foresights in the ways described.[61]

Uxmal

The Palace of the Governor at Uxmal.

Uxmal is a Mayan city in the Puuc Hills of Yucatán, Mexico. The Governor's Palace at Uxmal is often used as an exemplar of why it is important to combine ethnographic and alignment data. The palace is aligned with an azimuth of 118° on the pyramid of Cehtzuc. This alignment is also towards a southerly rising of Venus which occurs once every eight years. By itself this would not be sufficient to argue for a meaningful connection between the two events. The palace has to be aligned in one direction or another and why should the rising of Venus be any more important than the rising of the Sun, Moon, other planets, Sirius *et cetera*? The answer given is that not only does the palace point towards the rising of Venus, it is also covered in glyphs which stand for Venus and Mayan zodiacal constellations.[138] It is the combination of the alignment and the ethnography which suggests that the city was built with cosmic order in mind.

Fringe archaeoastronomy

> At least now we have all the archaeological facts to go along with the astronomers, the Druids, the Flat Earthers and all the rest.
>
> —Sir Jocelyn Stephens[139]

Archaeoastronomy owes something of this poor reputation among scholars to its occasional misuse to advance a range of pseudo-historical accounts. During the 1930s Otto S. Reuter compiled a study entitled *Germanische Himmelskunde*, or "Teutonic Skylore". The astronomical orientations of ancient monuments claimed by Reuter and his followers would place the ancient Germanic peoples ahead of the Ancient Near East in the field of astronomy, demonstrating the intellectual superiority of the "Aryans" (Indo-Europeans) over the Semites.[140]

Since the Nineteenth Century numerous scholars have sought to use archaeoastronomical calculations to demonstrate the antiquity of Ancient Indian Vedic culture, computing the dates of astronomical observations ambiguously described in ancient poetry to as early as 4000 BCE.[141] David Pingree, a historian of Indian astronomy, condemned "the scholars who perpetrate wild theories of prehistoric science and call themselves archaeoastronomers."[142]

More recently Gallagher,[143] Pyle,[144] and Fell[145] interpreted inscriptions in West Virginia as a description in Celtic Ogham alphabet of the supposed winter solstitial marker at the site. The controversial translation was supposedly validated by a problematic archaeoastronomical indication in which the winter solstice sun shone on an inscription of the sun at the site. Subsequent analyses criticized its cultural inappropriateness, as well as its linguistic and archeaoastronomical[146] claims, to describe it as an example of "cult archaeology".[147]

Archaeoastronomical organisations and publications

There are currently three academic organisations for scholars of archaeoastronomy. ISAAC—the International Society for Archaeoastronomy and Astronomy in Culture [148]—was founded in 1995 and now sponsors the Oxford conferences and *Archaeoastronomy — the Journal of Astronomy in Culture*. SEAC— La Société Européenne pour l'Astronomie dans la Culture [149]—is slightly older; it was created in 1992. SEAC holds annual conferences in Europe and publishes refereed conference proceedings on an annual basis. There is also SIAC— La Sociedad Interamericana de Astronomía en la Cultura [150], primarily a Latin American organisation which was founded in 2003.

Additionally the *Journal for the History of Astronomy* publishes many archaeoastronomical papers. For twenty-seven volumes it also published an annual supplement *Archaeoastronomy*.

Notes

[1] Sinclair 2006:13
[2] Ruggles 2005:19
[3] Ruggles 1999:155
[4] Iwaniszewski 2003, 7-10
[5] Aveni 1980
[6] Chiu & Morrison 1980
[7] Magli 2008
[8] McCluskey 2005
[9] Carlson 1999
[10] Bostwick 2006:13
[11] Michell, 2001:9-10
[12] Johnson, 1912:225
[13] Hoskin, 2001:7
[14] Michell, 2001:17-18
[15] Sinclair 2006:17
[16] Ruggles 2005:312-3
[17] Sinclair 2006:8

[18] Mackie 2006:243
[19] Hawkins 1976
[20] Atkinson 1966
[21] Thom 1988:9-10
[22] MacKie 1977
[23] Gingerich 2000
[24] Krupp 1979:18
[25] Hicks 1993
[26] Iwaniszewski 1995
[27] Zeilik 1985
[28] Zeilik 1986
[29] Milbraith 1999:8
[30] Broda 2000:233
[31] Hoskin 1996
[32] Ruggles 1993:ix
[33] Aveni 1982
[34] Heggie 1982
[35] Aveni, 1989a:xi–xiii
[36] Ruggles 2000
[37] Aveni 1981: 1-2
[38] Aveni 2003: 150
[39] McCluskey 2004
[40] Gummerman & Warburton 2005
[41] Bostwick 2006:3
[42] Bahn 1996:49
[43] McCluskey 2001
[44] Broda 2006
[45] Aldana 2007:14-15
[46] Poss 2005:97
[47] Schaefer 2006a:30
[48] Ruggles 1999: 3-9
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[50] Hoskin 2001:13-14.
[51] Ruggles & Saunders 1993:1-31
[52] Ruggles 2005:115-117
[53] Aveni 1986
[54] Hoskin 2001:2
[55] Ruggles & Saunders. 1993
[56] Iwaniszewski 2001
[57] Iwaniszewski 2003:7
[58] Aveni 1989:1
[59] Thom 1967: 107-117
[60] Ruggles 1999:25-29
[61] MacKie 1997
[62] MacKie 2006:362
[63] MacKie 2009
[64] Ruggles 1999:19-29
[65] Ruggles and Barclay 2000: 69-70
[66] Kintigh 1992
[67] Hoskin 2001
[68] Aveni 1989
[69] Kelley and Milone 2005:369-370
[70] Kelley and Milone 2005:367-8
[71] Milbraith 1988:70-71
[72] Aveni 2006:60-64
[73] Aveni 1979:175-183
[74] Aveni 1997:137-138
[75] Aveni 1989:5
[76] Bauer and Dearborn 1995

[77] Xu *et al.* 2000:1-7
[78] Schaefer 2006a:42-48
[79] Schaefer 2006b
[80] Iwaniszewski 2003
[81] Ruggles, 2005:112-113
[82] "*Brunton Pocket Transit Instruction Manual*, p. 22" (http://web.archive.org/web/20060304060347/http://www.brunton.com/manuals/current/Compasses/Transit.pdf) (PDF). . Retrieved 2008-03-02.
[83] Ruggles 2005:423-425
[84] Scholsser 2002
[85] Meller 2004
[86] van Driel-Murray 2002
[87] T. Freeth *et al.* 2006
[88] Inscriptiones Creticae III iv 11; Isager and Skydsgaard 1992:163
[89] Sofaer 2008
[90] Fountain 2005
[91] Robins & Ewing 1989
[92] Preston & Preston 2005: 115-118
[93] Aveni 1980:40-43
[94] Brandt and Williamson 1979
[95] Ruggles 2005:89
[96] Young 2005:23-25
[97] Cairns 2005
[98] Saethre 2007
[99] McCluskey 2005:78
[100] Ruggles 1999:18
[101] A.F. Aveni 1997:23-27
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[110] Aveni 1989b
[111] McCluskey 2000
[112] Salt & Boutsikas 2005
[113] Bauer & Dearborn 1995
[114] Urton 1981
[115] Krupp 1997a:196–9
[116] Hoskin 1999:15–6
[117] Hugh-Jones 1982:191-3
[118] Schaefer 2002
[119] Blomberg 2003, esp page 76
[120] Hannah 1994
[121] Krupp 1997a:252–3
[122] Dearborn, Seddon & Bauer, 1998
[123] Krupp 1988
[124] Rufinus
[125] Krupp. 1979:1
[126] Eogan 1991
[127] O'Kelly 1982:123-124
[128] Belmonte 2001
[129] Neugebauer 1980
[130] Spence 2000
[131] Hancock 1996:168
[132] Fairall 1999
[133] Krupp 1997b
[134] Krupp 1997a:267-269

[135] Parker Pearson *et al.* 2007
[136] Aveni 1997:65-66
[137] Jacobs 2006
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[139] Sir Jocelyn Stephens quoted in *The Times*, 8 July 1994, 8.
[140] Pedersen 1982:269
[141] Witzel 2001
[142] Pingree 1982:554-563, esp. p. 556
[143] Gallagher 1983
[144] Pyle 1983
[145] Fell 1983
[146] Wise 2003
[147] Lesser, 1983
[148] http://www.archaeoastronomy.org/
[149] http://www.archeoastronomy.org/
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External links

- Archaeoastronomy (http://library.thinkquest.org/C0118421/main.html) A Thinkquest website surveying archaeoastronomical sites across the world.
- Astronomy before History, by Clive Ruggles and Michael Hoskins (http://assets.cambridge.org/052157/2916/sample/0521572916web.pdf), a chapter from *The Cambridge Concise History of Astronomy,* Michael Hoskin ed., 1999
- Clive Ruggles's webpage: (http://www.cliveruggles.net/) images, bibliography, software, and synopsis of his course at the University of Leicester
- Space Imaging's Ancient Observatories gallery (http://www.spaceimaging.com/gallery/ancientobservatories/) — Satellite pictures of ancient observatories.
- Traditions of the Sun (http://www.traditionsofthesun.org/) — NASA and others exploring the world's ancient observatories.
- Ancient Observatories: Timeless Knowledge (http://sunearthday.nasa.gov/2005/images/ao_poster.pdf) NASA Poster on ancient (and modern) observatories.
- Mesoamerican Archaeoastronomy (http://jqjacobs.net/mesoamerica/meso_astro.html) - A Review of Contemporary Understandings of Prehispanic Astronomic Knowledge.

Societies

- ISAAC (http://www.archaeoastronomy.org/), The International Society for Archaeoastronomy and Astronomy in Culture.
- SEAC (http://www.archeoastronomy.org/) La Société Européenne pour l'Astronomie dans la Culture. Site in English.
- SIAC (http://www.arqueoastronomia.org/siac.htm) La Sociedad Interamericana de Astronomía en la Cultura.
- Society for the History of Astronomy (http://www.shastro.org.uk/)

Journals

- Archaeoastronomy and Ethnoastronomy News (http://www.wam.umd.edu/~tlaloc/archastro/ae.html)
- Archaeoastronomy: Supplement to the Journal for the History of Astronomy (http://www.shpltd.co.uk/aa.html)
- Archaeoastronomy: The Journal of Astronomy in Culture (http://www.utexas.edu/utpress/journals/jarch.html)
- Culture and Cosmos (http://www.cultureandcosmos.com/)
- Journal for the History of Astronomy (http://www.shpltd.co.uk/jha.html)

Observational astronomy

Observational astronomy


Mayall telescope at Kitt Peak National Observatory

Observational astronomy is a division of the astronomical science that is concerned with getting data, in contrast with theoretical astrophysics which is mainly concerned with finding out the measurable implications of physical models. It is the practice of observing celestial objects by using telescopes and other astronomical apparatus.

As a science, astronomy is somewhat hindered in that direct experiments with the properties of the distant universe are not possible. However, this is partly compensated by the fact that astronomers have a vast number of visible examples of stellar phenomena that can be examined. This allows for observational data to be plotted on graphs, and general trends recorded. Nearby examples of specific phenomena, such as variable stars, can then be used to infer the behavior of more distant representatives. Those distant yardsticks can then be employed to measure other phenomena in that neighborhood, including the distance to a galaxy.

Telescopes

Galileo Galilei was the first person known to have turned a telescope to the heavens and to record what he saw. Since that time, observational astronomy has made steady advances with each improvement in telescope technology.

A traditional division of observational astronomy is given by the region of the electromagnetic spectrum observed:

- Optical astronomy is the part of astronomy that uses optical components (mirrors, lenses and solid-state detectors) to observe light from near infrared to near ultraviolet wavelengths. Visible-light astronomy (using wavelengths that can be detected with the eyes, about 400 - 700 nm) falls in the middle of this range.
- Infrared astronomy deals with the detection and analysis of infrared radiation (this typically refers to wavelengths longer than the detection limit of silicon solid-state detectors, about 1 μm wavelength). The most common tool is the reflecting telescope but with a detector sensitive to infrared wavelengths. Space telescopes are used at certain wavelengths where the atmosphere is opaque, or to eliminate noise (thermal radiation from the atmosphere).
- Radio astronomy detects radiation of millimetre to dekametre wavelength. The receivers are similar to those used in radio broadcast transmission but much more sensitive. See also Radio telescopes.
- High-energy astronomy includes X-ray astronomy, gamma-ray astronomy, and extreme UV astronomy, as well as studies of neutrinos and cosmic rays.

Optical and radio astronomy can be performed with ground-based observatories, because the atmosphere is relatively transparent at the wavelengths being detected. Observatories are usually located at high altitudes so as to minimise the absorption and distortion caused by the Earth's atmosphere. Some wavelengths of infrared light are heavily absorbed by water vapor, so many infrared observatories are located in dry places at high altitude, or in space.

The atmosphere is opaque at the wavelengths used by X-ray astronomy, gamma-ray astronomy, UV astronomy and (except for a few wavelength "windows") far infrared astronomy, so observations must be carried out mostly from balloons or space observatories. Powerful gamma rays can, however be detected by the large air showers they produce, and the study of cosmic rays is a rapidly expanding branch of astronomy.

Optical telescopes

For much of the history of observational astronomy, almost all observation was performed in the visual spectrum with optical telescopes. While the Earth's atmosphere is relatively transparent in this portion of the electromagnetic spectrum, most telescope work is still dependent on seeing conditions and air transparency, and is generally restricted to the night time. The seeing conditions depend on the turbulence and thermal variations in the air. Locations that are frequently cloudy or suffer from atmospheric turbulence limit the resolution of observations. Likewise the presence of the full Moon can brighten up the sky with scattered light, hindering observation of faint objects.

For observation purposes, the optimal location for an optical telescope is undoubtedly in outer space. There the telescope can make observations without being affected by the atmosphere. However, at present it remains costly to lift telescopes into orbit. Thus the next best locations are certain mountain peaks that have a high number of cloudless days and generally possess good atmospheric conditions (with good seeing conditions). The peaks of the islands of Mauna Kea, Hawaii and La Palma possess these properties, as to a lesser extent do inland sites such as Llano de Chajnantor, Paranal, Cerro Tololo and La Silla in Chile. These observatory locations have attracted an assemblage of powerful telescopes, totalling many billion US dollars of investment.

The darkness of the night sky is an important factor in optical astronomy. With the size of cities and human populated areas ever expanding, the amount of artificial light at night has also increased. These artificial lights produce a diffuse background illumination that makes observation of faint astronomical features very difficult without special filters. In a few locations such as the state of Arizona and in the United Kingdom, this has led to campaigns for the reduction of light pollution. The use of hoods around street lights not only improves the amount of light directed toward the ground, but also helps reduce the light directed toward the sky.

Atmospheric effects (astronomical seeing) can severely hinder the resolution of a telescope. Without some means of correcting for the blurring effect of the shifting atmosphere, telescopes larger than about 15-20 cm in aperture can not achieve their theoretical resolution at visible wavelengths. As a result, the primary benefit of using very large telescopes has been the improved light-gathering capability, allowing very faint magnitudes to be observed. However the resolution handicap has begun to be overcome by adaptive optics, speckle imaging and interferometric imaging, as well as the use of space telescopes.

Astronomers have a number of observational tools that they can use to make measurements of the heavens. For objects that are relatively close to the Sun and Earth, direct and very precise position measurements can be made against a more distant (and thereby nearly stationary) background. Early observations of this nature were used to develop very precise orbital models of the various planets, and to determine their respective masses and gravitational perturbations. Such measurements led to the discovery of the planets Uranus, Neptune, and (indirectly) Pluto. They also resulted in an erroneous assumption of a fictional planet Vulcan within the orbit of Mercury (but the explanation of the precession of Mercury's orbit by Einstein is considered one of the triumphs of his general relativity theory).

Other instruments

In addition to examination of the universe in the optical spectrum, astronomers have increasingly been able to acquire information in other portions of the electromagnetic spectrum. The earliest such non-optical measurements were made of the thermal properties of the Sun. Instruments employed during a solar eclipse could be used to measure the radiation from the corona.

With the discovery of radio waves, radio astronomy began to emerge as a new discipline in astronomy. The long wavelengths of radio waves required much larger collecting dishes in order to make images with good resolution, and later led to the development of the multi-dish interferometer for making high-resolution aperture synthesis radio images (or "radio maps"). The development of the microwave horn receiver led to the discovery of the microwave background radiation associated with the big bang.

Radio astronomy has continued to expand its capabilities, even using radio astronomy satellites to produce interferometers with baselines much larger than the size of the Earth. However, the ever-expanding use of the radio spectrum for other uses is gradually drowning out the faint radio signals from the stars. For this reason, in the future radio astronomy might be performed from shielded locations, such as the far side of the Moon.

The last part of the twentieth century saw rapid technological advances in astronomical instrumentation. Optical telescopes were growing ever larger, and employing adaptive optics to partly negate atmospheric blurring. New telescopes were launched into space, and began observing the universe in the infrared, ultraviolet, x-ray, and gamma ray parts of the electromagnetic spectrum, as well as observing cosmic rays. Interferometer arrays produced the first extremely high-resolution images using aperture synthesis at radio, infrared and optical wavelengths. Orbiting instruments such as the Hubble Space Telescope produced rapid advances in astronomical knowledge, acting as the workhorse for visible-light observations of faint objects. New space instruments under development are expected to directly observe planets around other stars, perhaps even some Earth-like worlds.

In addition to telescopes, astronomers have begun using other instruments to make observations. Huge underground tanks have been built to detect neutrino emissions from the Sun and supernovae. Gravity wave detectors are being designed that may capture events such as collisions of massive objects such as neutron stars. Robotic spacecraft are also being increasingly used to make highly detailed observations of planets within the solar system, so that the field of planetary science now has significant cross-over with the disciplines of geology and meteorology.

Observation tools

The key instrument of nearly all modern observational astronomy is the telescope. This serves the dual purposes of gathering more light so that very faint objects can be observed, and magnifying the image so that small and distant objects can be observed. For optical astronomy, the optical components used in a telescope have very exacting requirements which require great precision in their construction. Typical requirements for grinding and polishing a curved mirror, for example, require the surface to be within a fraction of a wavelength of light of a particular conic shape. Many modern "telescopes" actually consist of arrays of telescopes working together to provide higher resolution through aperture synthesis.

Large telescopes are housed in domes, both to protect them from the weather and to stabilize the environmental conditions. For example, if the temperature is different from one side of the telescope to the other, the shape of the structure will change, due to thermal expansion, pushing optical elements out of position, and affecting the image. For this reason, the domes are usually bright white (titanium dioxide) or unpainted metal. Domes are often opened around sunset, long before observing can begin, so that air can circulate and bring the entire telescope to the same temperature as the surroundings. In order to prevent wind-buffet or other vibrations affecting observations, it is standard practice to mount the telescope on a concrete pier whose foundations are entirely separate from those of the surrounding dome/building.

In order to do almost any scientific work, telescopes must keep track of objects as they wheel across the visible sky. In other words, they must smoothly compensate for the rotation of the Earth. Until the advent of computer controlled drive mechanisms, the standard solution was some form of equatorial mount, and for small telescopes this is still the norm. However, this is a structurally poor design and becomes more and more cumbersome as the diameter and weight of the telescope increases. The world's largest equatorial mounted telescope is the 200 inch (5.1 m) Hale Telescope, whereas recent 8-10 m telescopes use the structurally better Altazimuth mount, and are actually physically *smaller* than the Hale, despite the larger mirrors. As of 2006, there are design projects underway for gigantic alt-az telescopes: the Thirty Metre Telescope [1], and the 100 m diameter Overwhelmingly Large Telescope[2]

Amateur astronomers use such instruments as the Newtonian reflector, the Refractor and the increasingly popular Maksutov telescope.

The photograph has served a critical role in observational astronomy for over a century, but in the last 30 years it has been largely replaced for imaging applications by digital sensors such as CCDs and CMOS chips. Specialist areas of astronomy such as photometry and interferometry have utilised electronic detectors for a much longer period of time. Astrophotography uses specialised photographic film (or usually a glass plate coated with photographic emulsion), but there are a number of drawbacks, particularly a low quantum efficiency, of the order of 3%, whereas CCDs can be tuned for a QE >90% in a narrow band. Almost all modern telescope instruments are electronic arrays, and older telescopes have been either been retrofitted with these instruments or closed down. Glass plates are still used in some applications, such as surveying, because the resolution possible with a chemical film is much higher than any electronic detector yet constructed.

Prior to the invention of photography, all astronomy was done with the naked eye. However, even before films became sensitive enough, scientific astronomy moved entirely to film, because of the overwhelming advantages:

- The human eye discards what it sees from split-second to split-second, but photographic film gathers more and more light for as long as the shutter is open.
- The resulting image is permanent, so many astronomers can use the same data.
- It is possible to see objects as they change over time (SN 1987A is a spectacular example).

The blink comparator is an instrument that is used to compare two nearly identical photographs made of the same section of sky at different points in time. The comparator alternates illumination of the two plates, and any changes are revealed by blinking points or streaks. This instrument has been used to find asteroids, comets, and variable stars.

The position or cross-wire micrometer is an implement that has been used to measure double stars. This consists of a pair of fine, movable lines that can be moved together or apart. The telescope lens is lined up on the pair and oriented using position wires that lie at right angles to the star separation. The movable wires are then adjusted to match the two star positions. The separation of the stars is then read off the instrument, and their true separation determined based on the magnification of the instrument.

A vital instrument of observational astronomy is the spectrograph. The absorption of specific wavelengths of light by elements allows specific properties of distant bodies to be observed. This capability has resulted in the discovery of the element of helium in the Sun's emission spectrum, and has allowed astronomers to determine a great deal of information concerning distant stars, galaxies, and other celestial bodies. Doppler shift (particularly "redshift") of spectra can also be used to determine the radial motion or distance with respect to the Earth.

Early spectrographs employed banks of prisms that would split the light into a broad spectrum. Later the grating spectrograph was developed, which reduced the amount of light loss compared to prisms and provided higher spectral resolution. The spectrum can be photographed in a long exposure, allowing the spectrum of faint objects (such as distant galaxies) to be measured.

Stellar photometry came into use in 1861 as a means of measuring stellar colors. This technique measured the magnitude of a star at specific frequency ranges, allowing a determination of the overall color, and therefore temperature of a star. By 1951 an internationally standardized system of UBV-magnitudes (*U*ltraviolet-*B*lue-*V*isual) was adopted.

Photoelectric photometry using the CCD is now frequently used to make observations through a telescope. These sensitive instruments can record the image nearly down to the level of individual photons, and can be designed to view in parts of the spectrum that are invisible to the eye. The ability to record the arrival of small numbers of photons over a period of time can allow a degree of computer correction for atmospheric effects, sharpening up the image. Multiple digital images can also be combined to further enhance the image. When combined with the adaptive optics technology, image quality can approach the theoretical resolution capability of the telescope.

Filters are used to view an object at particular frequencies or frequency ranges. Multilayer film filters can provide very precise control of the frequencies transmitted and blocked, so that, for example, objects can be viewed at a particular frequency emitted only by excited hydrogen atoms. Filters can also be used to partially compensate for the effects of light pollution by blocking out unwanted light. Polarization filters can also be used to determine if a source is emitting polarized light, and the orientation of the polarization.

Observing

Astronomers observe a wide range of astronomical sources, including high-redshift galaxies, AGNs, the afterglow from the Big Bang and many different types of stars and protostars.

A variety of data can be observed for each object. The position coordinates locate the object on the sky using the techniques of spherical astronomy, and the magnitude determines its brightness as seen from the Earth. The relative brightness in different parts of the spectrum yields information about the temperature and physics of the object. Photographs of the spectra allow the chemistry of the object to be examined.

Parallax shifts of a star against the background can be used to determine the distance, out to a limit imposed by the resolution of the instrument. The radial velocity of the star and changes in its position over time (proper motion) can be used to measure its velocity relative to the Sun. Variations in the brightness of the star give evidence of instabilities in the star's atmosphere, or else the presence of an occulting companion. The orbits of binary stars can be used to measure the relative masses of each companion, or the total mass of the system. Spectroscopic binaries can be found by observing doppler shifts in the spectrum of the star and its close companion.

Stars of identical masses that are formed at the same time and under the similar conditions will typically have nearly identical observed properties. Observing a mass of closely associated stars, such as in a globular cluster, allows data to be assembled about the distribution of stellar types. These tables can then be used to infer the age of the association.

For distant galaxies and AGNs observations are made of the overall shape and properties of the galaxy, as well as the groupings in which they are found. Observations of certain types of variable stars and supernovae of known luminosity, called standard candles, in other galaxies allows the inference of the distance to the host galaxy. The expansion of space causes the spectra of these galaxies to be shifted, depending on the distance, and modified by the doppler effect of the galaxy's radial velocity. Both the size of the galaxy and its redshift can be used to infer something about the distance of the galaxy. Observations of large numbers of galaxies are referred to as redshift surveys, and are used to model the evolution of galaxy forms.

Related lists

- List of observatories
- List of radio telescopes

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[2] http://www.eso.org/projects/owl/

Radio astronomy

The Very Large Array, a radio interferometer in New Mexico, USA

Radio astronomy is a subfield of astronomy that studies celestial objects at radio frequencies. The initial detection of radio waves from an astronomical object was made in the 1930s, when Karl Jansky observed radiation coming from the Milky Way. Subsequent observations have identified a number of different sources of radio emission. These include stars and galaxies, as well as entirely new classes of objects, such as radio galaxies, quasars, pulsars, and masers. The discovery of the cosmic microwave background radiation, which provided compelling evidence for the Big Bang, was made through radio astronomy.

Radio astronomy is conducted using large radio antennae referred to as radio telescopes, that are either used singularly, or with multiple linked telescopes utilizing the techniques of radio interferometry and aperture synthesis. The use of interferometry allows radio astronomy to achieve high angular resolution, as the resolving power of an interferometer is set by the distance between its components, rather than the size of its components.

History

Four large antennas for the ALMA thrust to the sky at the Operations Support Facility (OSF).

Before Jansky observed the Milky Way in the 1930s, physicists speculated that radio waves could be observed from astronomical sources. In the 1860s, James Clerk Maxwell's equations had shown that electromagnetic radiation is associated with electricity and magnetism, and could exist at any wavelength. Several attempts were made to detect radio emission from the Sun by experimenters such as Nikola Tesla and Oliver Lodge, but those attempts were unable to detect any emission due to technical limitations of their instruments.[1]

Karl Jansky made the discovery of the first astronomical radio source serendipitously in the early 1930s. As an engineer with Bell Telephone Laboratories, he was investigating static that interfered with short wave transatlantic voice transmissions. Using a large directional antenna, Jansky noticed that his analog pen-and-paper recording system kept recording a repeating signal of unknown origin. Since the signal peaked about every 24 hours, Jansky originally suspected the source of the interference was the Sun crossing the view of his directional antenna. Continued analysis showed that the source was not following the 24 hour daily cycle of the Sun exactly, but instead repeating on a cycle of 23 hours and 56 minutes. Jansky discussed the puzzling phenomena with his friend, astrophysicist and teacher Albert Melvin Skellett, who pointed out that the signal seemed to be typical of an astronomical source "fixed" in relationship to the stars on the celestial sphere and rotating in sync with sidereal time.[2] By comparing his observations with optical astronomical maps, Jansky eventually concluded that the radiation was coming from the Milky Way, and that it was strongest in the direction of the center of the galaxy, in the constellation of Sagittarius.[3] He also concluded that since he was unable to detect radio noise from the Sun, the strange radio interference may be generated by interstellar gas and dust in the galaxy.[2] He announced his discovery in 1933. Jansky wanted to investigate the radio waves from the Milky Way in further detail, but Bell Labs re-assigned him to another project, so he did no further work in the field of astronomy. However, his pioneering efforts in the field of radio astronomy have been recognized by the naming of the fundamental unit of flux density, the Jansky (Jy), after him.

Grote Reber was inspired by Jansky's work, and built a parabolic radio telescope 9m in diameter in his own backyard in 1937. He began by repeating Jansky's observations, and went on to conduct the first sky survey in the radio frequencies.[4] On February 27, 1942, J.S. Hey, a British Army research officer, made the first detection of radio waves emitted by the Sun.[5] By the early 1950s, Martin Ryle and Antony Hewish at Cambridge University had used the Cambridge Interferometer to map the radio sky, producing the famous 2C and 3C surveys of radio sources.

Techniques

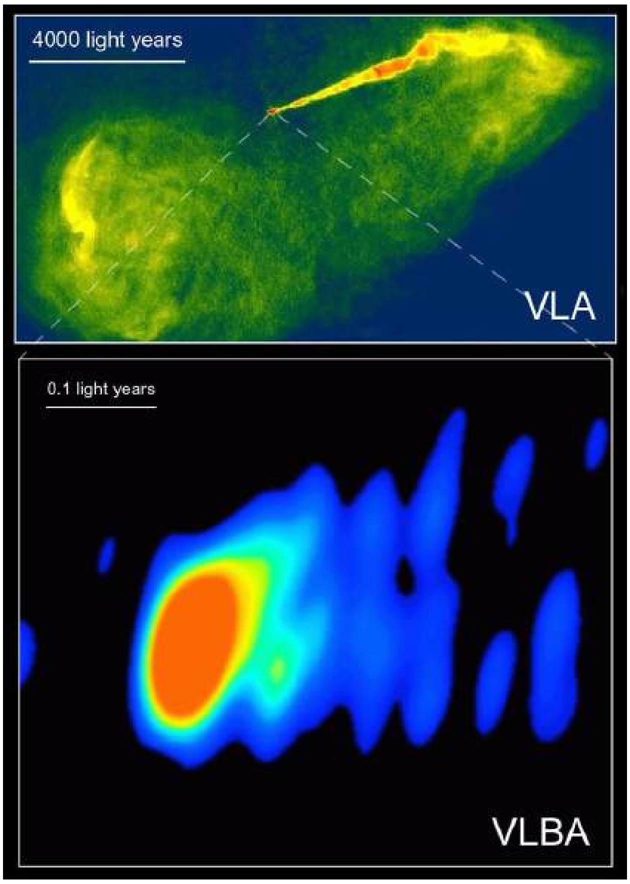
Radio astronomers use different techniques to observe objects in the radio spectrum. Instruments may simply be pointed at an energetic radio source to analyze its emission. To “image” a region of the sky in more detail, multiple overlapping scans can be recorded and piece together in a mosaic image. The type of instruments used depends on the strength of the signal and the amount of detail needed.

Observations from the Earth's surface are limited to wavelengths that can pass through the atmosphere. At low frequencies, or long wavelengths, transmission is limited by the ionosphere, which reflects waves with frequencies less than its characteristic plasma frequency. Water vapor interferes with radio astronomy at higher frequencies, which has led to building radio observatories that conduct observations at millimeter wavelengths at very high and dry sites, in order to minimize the water vapor content in the line of sight.

Radio telescopes

Radio telescopes may need to be extremely large in order to receive signals with low signal-to-noise ratio. Also since angular resolution is a function of the diameter of the "objective" in proportion to the wavelength of the electromagnetic radiation being observed, *radio telescopes* have to be much larger in comparison to their optical counterparts. For example a 1 meter diameter optical telescope is two million times bigger than the wavelength of light observed giving it a resolution of roughly 0.3 arc seconds, whereas a radio telescope "dish" many times that size may, depending on the wavelength observed, only be able to resolve an object the size of the full moon (30 minutes of arc).

Radio interferometry



An **optical** image of the galaxy M87 (HST), a radio image of same galaxy using **Interferometry** (Very Large Array-**VLA**), and an image of the center section (**VLBA**) using a *Very Long Baseline Array* (Global VLBI) consisting of antennas in the US, Germany, Italy, Finland, Sweden and Spain. The jet of particles is suspected to be powered by a black hole in the center of the galaxy.

The difficulty in achieving high resolutions with single radio telescopes led to radio interferometry, developed by British radio astronomer Martin Ryle and Australian-born engineer, radiophysicist, and radio astronomer Joseph Lade Pawsey and Ruby Payne-Scott in 1946. Surprisingly the first use of a radio interferometer for an astronomical observation was carried out by Payne-Scott, Pawsey and Lindsay McCready on 26 January 1946 using a SINGLE converted radar antenna (broadside array) at 200 MHz near Sydney, Australia. This group used the principle of a sea-cliff interferometer in which the antenna (formerly a WWII radar) observed the sun at sunrise with interference arising from the direct radiation from the sun and the reflected radiation from the sea. With this baseline of almost 200 meters, the authors determined that the solar radiation during the burst phase was much smaller than the solar disk and arose from a region associated with a large sunspot group. The Australia group laid out the principles of aperture synthesis in their ground-breaking paper submitted in mid 1946 and published in 1947. The use of a sea-cliff interferometer had been demonstrated by numerous groups in Australia, Iran and the UK during World War II, who had observed interference fringes (the direct radar return radiation and the reflected signal from the sea) from incoming aircraft.

The Cambridge group of Ryle and Vonberg observed the sun at 175 MHz for the first time in mid July 1946 with a Michelson interferometer consisting of a two radio antennas with spacings of some tens of meters up to 240 meters. They showed that the radio radiation was smaller than 10 arc min in size and also detected circular polarization in the Type I bursts. Two other groups had also detected circular polarization at about the same time (David Martyn in Australia and Edward Appleton with J. Stanley Hey in the UK).

Modern Radio interferometers consist of widely separated radio telescopes observing the same object that are connected together using coaxial cable, waveguide, optical fiber, or other type of transmission line. This not only increases the total signal collected, it can also be used in a process called Aperture synthesis to vastly increase resolution. This technique works by superposing (**interfering**) the signal waves from the different telescopes on the principle that waves that coincide with the same phase will add to each other while two waves that have opposite phases will cancel each other out. This creates a combined telescope that is the size of the antennas furthest apart in the array. In order to produce a high quality image, a large number of different separations between different telescopes are required (the projected separation between any two telescopes as seen from the radio source is called a **baseline**) - as many different baselines as possible are required in order to get a good quality image. For example the Very Large Array has 27 telescopes giving 351 independent baselines at once.

Very Long Baseline Interferometry

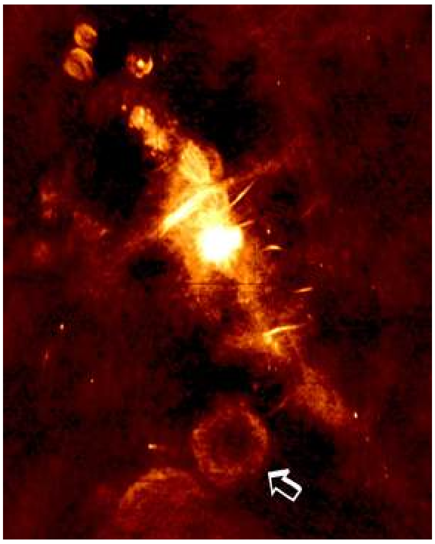
Beginning in the 1970s, improvements in the stability of radio telescope receivers permitted telescopes from all over the world (and even in Earth orbit) to be combined to perform Very Long Baseline Interferometry. Instead of physically connecting the antennas, data received at each antenna is paired with timing information, usually from a local atomic clock, and then stored for later analysis on magnetic tape or hard disk. At that later time, the data is correlated with data from other antennas similarly recorded, to produce the resulting image. Using this method it is possible to synthesise an antenna that is effectively the size of the Earth. The large distances between the telescopes enable very high angular resolutions to be achieved, much greater in fact than in any other field of astronomy. At the highest frequencies, synthesised beams less than 1 milliarcsecond are possible.

The pre-eminent VLBI arrays operating today are the Very Long Baseline Array (with telescopes located across North America) and the European VLBI Network (telescopes in Europe, China, South Africa and Puerto Rico). Each array usually operates separately, but occasional projects are observed together producing increased sensitivity. This is referred to as Global VLBI. There is also a VLBI network, the Long Baseline Array, operating in Australia.

Since its inception, recording data onto hard media has been the only way to bring the data recorded at each telescope together for later correlation. However, the availability today of worldwide, high-bandwidth optical fibre networks makes it possible to do VLBI in real time. This technique (referred to as e-VLBI) was pioneered by the EVN (European VLBI Network) who now perform an increasing number of scientific e-VLBI projects per year.[6]

Astronomical sources

Radio astronomy has led to substantial increases in astronomical knowledge, particularly with the discovery of several classes of new objects, including pulsars, quasars and radio galaxies. This is because radio astronomy allows us to see things that are not detectable in optical astronomy. Such objects represent some of the most extreme and energetic physical processes in the universe.



A radio image of the central region of the Milky Way galaxy. The arrow indicates a supernova remnant which is the location of a newly-discovered transient, bursting low-frequency radio source GCRT J1745-3009.

The cosmic microwave background radiation was also first detected using radio telescopes. However, radio telescopes have also been used to investigate objects much closer to home, including observations of the Sun and solar activity, and radar mapping of the planets.

Other sources include:

- Sun
- Sagittarius A, the galactic center of the Milky Way
- Active galactic nuclei and pulsars have jets of charged particles which emit synchrotron radiation
- Merging galaxy clusters often show diffuse radio emission [7]
- Supernova remnants can also show diffuse radio emission
- The Cosmic microwave background is blackbody radio emission
- Jupiter

Notes

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Infrared astronomy

Infrared astronomy is the branch of astronomy and astrophysics that studies astronomical objects visible in infrared (IR) radiation. The wavelength of infrared light ranges from 0.75 to 300 micrometers. Infrared falls in between visible radiation, which ranges from 380 to 750 nanometers, and submillimeter waves.

Carina Nebula in infrared light captured by the Hubble's Wide Field Camera 3.

Infrared astronomy began in the 1830s, a few decades after the discovery of infrared light by William Herschel in 1800. Early progress was limited, and it was not until the early 20th century that conclusive detections of astronomical objects other than the Sun and Moon were detected in infrared light. After a number of discoveries were made in the 1950s and 1960s in radio astronomy, astronomers realized the information available outside of the visible wavelength range, and modern infrared astronomy was established.

Infrared and optical astronomy are often practiced using the same telescopes, as the same mirrors or lenses are usually effective over a wavelength range that includes both visible and infrared light. Both fields also use solid state detectors, though not the specific type of solid state detectors used are different. Infrared light is absorbed at many wavelengths by water vapor in the Earth's atmosphere, so most infrared telescopes are at high elevations in dry places, above as much of the atmosphere as possible. There are also infrared observatories in space, including the Spitzer Space Telescope and the Herschel Space Observatory.

History

SOFIA is an infrared telescope in an aircraft, shown here in a 2009 test

The discovery of infrared radiation is attributed to William Herschel, who performed an experiment where he placed a thermometer in sunlight of different colors after it passed through a prism. He noticed that the temperature increase induced by sunlight was highest *outside* the visible spectrum, just beyond the red color. That the temperature increase was highest at infrared wavelengths was due to the spectral index of the prism rather than properties of the Sun, but the fact that there was any temperature increase at all prompted Herschel to deduce that there was invisible radiation from the Sun. He dubbed this radiation "calorific rays", and went on show that it could be reflected, transmitted, and absorbed just like visible light.[1]

Efforts were made starting in the 1830s and continuing through the 19th century to detect infrared radiation from other astronomical sources. Radiation from the Moon was first detected in 1873 by William Parsons, 3rd Earl of Rosse. Ernest Fox Nichols use a modified Crookes radiometer in an attempt to detect infrared radiation from Arcturus and Vega, but Nichols deemed the results inconclusive. Even so, the ratio of flux he reported for the two stars is consistent with the modern value, so George Rieke gives Nichols credit for the first detection of a star other than our own in the infrared.[2]

The field of infrared astronomy continued to develop slowly in the early 20th century, as Seth Barnes Nicholson and Edison Pettit developed thermopile detectors capable of accurate infrared photometry and sensitive to a few hundreds of stars. The field was mostly neglected by traditional astronomers though until the 1960s, with most scientists who practiced infrared astronomy having actually been trained physicists. The success of radio astronomy during the 1950s and 1960s, combined with the improvement of infrared detector technology, prompted more astronomers to take notice, and infrared astronomy became well established as a subfield of astronomy.[2]

Modern infrared astronomy

Infrared radiation with wavelengths just longer than visible light, known as near-infrared, behaves in a very similar way to visible light, and can be detected using similar solid state devices. For this reason, the near infrared region of the spectrum is commonly incorporated as part of the "optical" spectrum, along with the near ultraviolet. Many optical telescopes, such as those at Keck Observatory, operate effectively in the near infrared as well as at visible wavelengths. The far-infrared extends to submillimeter wavelengths, which are observed by telescopes such as the James Clerk Maxwell Telescope at Mauna Kea Observatory.

Like all other forms of electromagnetic radiation, infrared is utilized by astronomers to study the universe. Infrared telescopes, which includes most major optical telescopes as well as a few dedicated infrared telescopes, need to be chilled with liquid nitrogen and shielded from warm objects. The reason for this is that objects with temperatures of a few hundred Kelvin emit most of their thermal energy at infrared wavelengths. If infrared detectors were not kept cooled, the radiation from the detector itself would contribute noise that would dwarf the radiation from any celestial source. This is particularly important in the mid-infrared and far-infrared regions of the spectrum.

To achieve higher angular resolution, some infrared telescopes are combined to form astronomical interferometers. The effective resolution of an interferometer is set by the distance between the telescopes, rather than the size of the individual telescopes. When used together with adaptive optics, infrared interferometers, such as two 10 meter telescopes at Keck Observatory or the four 8.2 meter telescopes that make up the Very Large Telescope Interferometer, can achieve high angular resolution.

The principal limitation on infrared sensitivity from ground-based telescopes is the Earth's atmosphere. Water vapor absorbs a significant amount of infrared radiation, and the atmosphere itself emits at infrared wavelengths. For this reason, most infrared telescopes are built in very dry places at high altitude, so that they are above most of the water vapor in the atmosphere. Suitable locations on Earth include Mauna Kea Observatory at 4205 meters above sea level, the ALMA site at 5000 m in Chile and regions of high altitude ice-desert such as Dome C in Antarctic. Even at high altitudes, the transparency of the Earth's altitude is limited except in infrared windows, or wavelengths where the Earth's atmosphere is transparent.[3] The main infrared windows are listed below:

Wavelength range (micrometres)	Astronomical bands	Telescopes
0.65 to 1.0	R and I bands	All major optical telescopes
1.25	J band	Most major optical telescopes and most dedicated infrared telescopes
1.65	H band	Most major optical telescopes and most dedicated infrared telescopes
2.2	K band	Most major optical telescopes and most dedicated infrared telescopes
3.45	L band	Most dedicated infrared telescopes and some optical telescopes
4.7	M band	Most dedicated infrared telescopes and some optical telescopes
10	N band	Most dedicated infrared telescopes and some optical telescopes
20	Q band	Some dedicated infrared telescopes and some optical telescopes
450	submillimeter	Submillimeter telescopes

As is the case for visible light telescopes, space is the ideal place for infrared telescopes. In space, images from infrared telescopes can achieve higher resolution, as they do not suffer from blurring caused by the Earth's atmosphere, and are also free from absorption caused by the Earth's atmosphere. Current infrared telescopes in space include the Herschel Space Observatory, the Spitzer Space Telescope, and the Wide-field Infrared Survey Explorer. Since putting telescopes in orbit is expensive, there are also airborne observatories, such as the Stratospheric Observatory for Infrared Astronomy and the Kuiper Airborne Observatory. These observatories place telescopes above most, but not all, of the atmosphere, which means there is absorption of infrared light from space by water vapor in the atmosphere.

Infrared technology

One of the most common infrared detector arrays used at research telescopes is HgCdTe arrays. These operate well between 0.6 and 5 micrometre wavelengths. For longer wavelength observations or higher sensitivity other detectors may be used, including other narrow gap semiconductor detectors, low temperature bolometer arrays or photon-counting Superconducting Tunnel Junction arrays.

Special requirements for infrared astronomy include: very low dark currents to allow long integration times, associated low noise readout circuits and sometimes very high pixel counts.

Low temperature is often achieved by a coolant, which can run out.[4] Space missions have either ended or shifted to "warm" observations when the coolant supply used up.[4] For example, WISE ran out of coolant in October 2010, about ten months after being launched.[4] (See also NICMOS, Spitzer Space Telescope)

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[2] Rieke, George H. (2009). "History of infrared telescopes and astronomy". *Experimental Astronomy* **25** (1-3): 125–141. Bibcode 2009ExA....25..125R. doi:10.1007/s10686-009-9148-7.

[3] "IR Atmospheric Windwows" (http://coolcosmos.ipac.caltech.edu/cosmic_classroom/ir_tutorial/irwindows.html). . Retrieved 2009-04-09.

[4] Debra Werner - **Last-minute Reprieve Extends WISE Mission** (5 October, 2010) - Space News (http://www.spacenews.com/civil/101005-last-minute-reprieve.html)

External links

- Caltech IR tutorial (http://coolcosmos.ipac.caltech.edu/cosmic_classroom/ir_tutorial/)

Visible-light astronomy

Visible-light astronomy encompasses a wide variety of observations via telescopes that are sensitive in the range of visible light (optical telescopes). It includes *imaging*, where a picture of some sort is made of the object; *photometry*, where the amount of light coming from an object is measured, *spectroscopy*, where the distribution of that light with respect to its wavelength is measured, and *polarimetry* where the polarisation state of that light is measured.

An example of spectroscopy is the study of spectral lines to understand of what kind of matter light is going through. Visible astronomy also includes looking up at night (skygazing).

Visible-light astronomy is part of optical astronomy.

Ultraviolet astronomy

Ultraviolet astronomy is generally used to refer to observations of electromagnetic radiation at ultraviolet wavelengths between approximately 10 and 320 nanometres; shorter wavelengths—higher energy photons—are studied by X-ray astronomy and gamma ray astronomy.[1] Light at these wavelengths is absorbed by the Earth's atmosphere, so observations at these wavelengths must be performed from the upper atmosphere or from space.[1]

A GALEX image of the spiral galaxy Messier 81 in ultraviolet light. Credit:GALEX/NASA/JPL-Caltech.

Ultraviolet line spectrum measurements are used to discern the chemical composition, densities, and temperatures of the interstellar medium, and the temperature and composition of hot young stars. UV observations can also provide essential information about the evolution of galaxies.

The ultraviolet Universe looks quite different from the familiar stars and galaxies seen in visible light. Most stars are actually relatively cool objects emitting much of their electromagnetic radiation in the visible part of the spectrum. Ultraviolet radiation is the signature of hotter objects, typically in the early and late stages of their evolution. If we could see the sky in ultraviolet light, most stars would fade in prominence. We would see some very young massive stars and some very old stars and galaxies, growing hotter and producing higher-energy radiation near their birth or death. Clouds of gas and dust would block our vision in many directions along the Milky Way.

The Hubble Space Telescope and FUSE have been the most recent major space telescopes to view the near and far UV spectrum of the sky, though other UV instruments have flown on sounding rockets and the Space Shuttle.

Ultraviolet space telescopes

- - Astron-1
- - Astrosat
- - Astronomical Netherlands Satellite
- (ESA) - Extreme ultraviolet Imaging Telescope
- - FUSE
- - GALEX
- (ESA) - Hubble Space Telescope
- (ESA) - International Ultraviolet Explorer
- - Orbiting Astronomical Observatory
- - Swift Gamma-Ray Burst Mission

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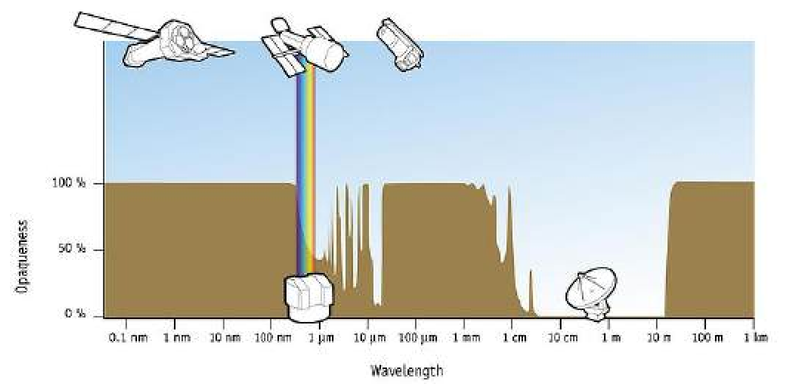
X-ray astronomy



X-rays start at ~0.008 nm and extend across the electromagnetic spectrum to ~8 nm, over which Earth's atmosphere is opaque.

X-ray astronomy is an observational branch of astronomy which deals with the study of X-ray emission from celestial objects. X-radiation is absorbed by the Earth's atmosphere, so instruments to detect X-rays must be taken to high altitude by balloons, sounding rockets, and satellites. X-ray astronomy is part of space science.

X-ray emission is expected in sources which contain an extremely hot gas at temperatures from a million to hundred million kelvins. In general, this occurs in objects where the atoms and/or electrons have a very high energy. The discovery of the first cosmic X-ray source in 1962 came as a surprise. This source is called Scorpius X-1, the first X-ray source found in the constellation Scorpius. Based on discoveries in this new field, Riccardo Giacconi received the Nobel Prize in Physics in 2002. It was found that the X-ray emission of Sco X-1 was 10,000 times greater than its optical emission, based on a precise location obtained with a modulation collimator - a specific type of coded aperture imager. In addition, the energy output in X-rays is 100,000 times greater than the total emission of the Sun in all wavelengths. It is now known that such X-ray sources are compact stars, such as neutron stars and black holes (in which case the material that falls into the black hole emits the x-rays, not the black hole itself). The energy source is gravity. Gas is heated by the fall in the strong gravitational field of celestial objects.

Many thousands of X-ray sources are known. In addition, it appears that the space between galaxies in a cluster of galaxies is filled with a very hot, but very dilute gas at a temperature between 10 and 100 megakelvins (MK). The total amount of hot gas is five to ten times the total mass in the visible galaxies.

Sounding rocket flights

A detector is placed in the nose cone section of a sounding rocket and launched above the atmosphere. This was first done at White Sands Missile Range in New Mexico with a V-2 rocket on January 28, 1949. X-rays from the Sun were detected by the USA Naval Research Laboratory Blossom experiment on board.[1] An Aerobee 150 rocket launched on June 12, 1962 detected the first X-rays from other celestial sources (Scorpius X-1).[2] The largest drawback to rocket flights is their very short duration (just a few minutes above the atmosphere before the rocket falls back to Earth) and their limited field of view. A rocket launched from the United States will not be able to see sources in the southern sky; a rocket launched from Australia will not be able to see sources in the northern sky.

X-ray Quantum Calorimeter (XQC) project

In astronomy, the **interstellar medium** (or **ISM**) is the gas and dust that pervade interstellar space: the matter that exists between the star systems within a galaxy. It fills interstellar space and blends smoothly into the surrounding intergalactic space. The interstellar medium consists of an extremely dilute (by terrestrial standards) mixture of ions, atoms, molecules, larger dust grains, cosmic rays, and (galactic) magnetic fields.[3] The energy that occupies the same volume, in the form of electromagnetic radiation, is the **interstellar radiation field**.

A launch of the Black Brant 9 Microcalorimeter at the turn of the century as a part of the joint undertaking by the University of Wisconsin-Madison and NASA's Goddard Space Flight Center known as the X-ray Quantum Calorimeter (XQC) project.

Of interest is the hot ionized medium (HIM) consisting of coronal gas at 10^6-10^7 K which emits X-rays. The ISM is turbulent and therefore full of structure on all spatial scales. Stars are born deep inside large complexes of molecular clouds, typically a few parsecs in size. During their lives and deaths, stars interact physically with the ISM. Stellar winds from young clusters of stars (often with giant or supergiant HII regions surrounding them) and shock waves created by supernovae inject enormous amounts of energy into their surroundings, which leads to hypersonic turbulence. The resultant structures – of varying sizes – can be observed, such as stellar wind bubbles and superbubbles of hot gas, seen by X-ray satellite telescopes. The Sun is currently traveling through the Local Interstellar Cloud, a denser region in the low-density Local Bubble.

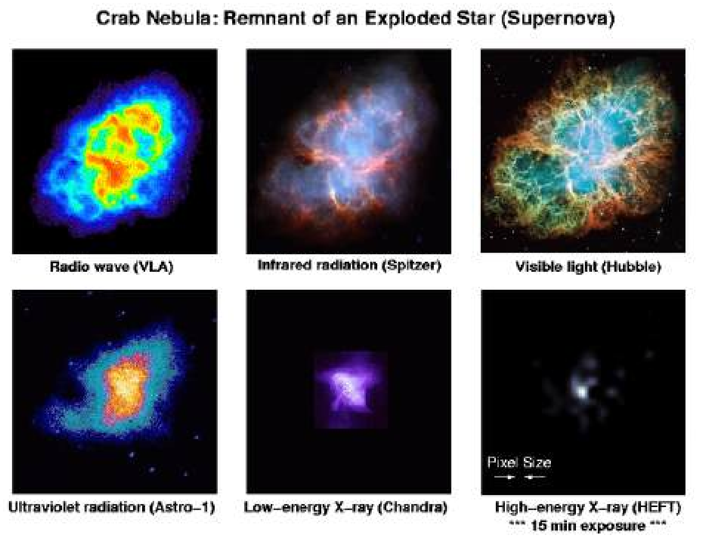
To measure the spectrum of the diffuse X-ray emission from the interstellar medium over the energy range 0.07 to 1 keV, NASA launched a Black Brant 9 from White Sands Missile Range, New Mexico on May 1, 2008.[4] The Principal Investigator for the mission is Dr. Dan McCammon of the University of Wisconsin.

Balloons

Balloon flights can carry instruments to altitudes of up to 40 km above sea level, where they are above as much as 99.997% of the Earth's atmosphere. Unlike a rocket where data are collected during a brief few minutes, balloons are able to stay aloft for much longer. However, even at such altitudes, much of the X-ray spectrum is still absorbed. X-rays with energies less than 35 keV (5,600 aJ) cannot reach balloons. On July 21, 1964, the Crab Nebula supernova remnant is discovered to be a hard X-ray (15 - 60 keV) source by a scintillation counter flown on a balloon launched from Palestine, Texas, USA. This was likely the first balloon-based detection of X-rays from a discrete cosmic X-ray source.[5]

High-energy focusing telescope

The high-energy focusing telescope (HEFT) is a balloon-borne experiment to image astrophysical sources in the hard X-ray (20-100 keV) band.[6] Its maiden flight took place in May 2005 from Fort Sumner, New Mexico, USA. The angular resolution of HEFT is ~1.5'. HEFT makes use of tungsten-silicon multilayer coatings to extend the reflectivity of nested grazing-incidence mirrors beyond 10 keV. HEFT has an energy resolution of 1.0 keV full width at half maximum at 60 keV. HEFT was launched for a 25-hour balloon flight in May 2005. The instrument performed within specification and observed Tau X-1, the Crab Nebula.



The Crab Nebula is a remnant of an exploded star. This is the Crab Nebula in various energy bands, including a hard X-ray image from the HEFT data taken during its 2005 observation run. Each image is 6′ wide.

High-resolution gamma-ray and hard X-ray spectrometer (HIREGS)

One of the recent balloon-borne experiments was called the High-resolution gamma-ray and hard X-ray spectrometer (HIREGS).[7] It was first launched from McMurdo Station, Antarctica in December 1991, when steady winds carried the balloon on a circumpolar flight lasting for about two weeks.

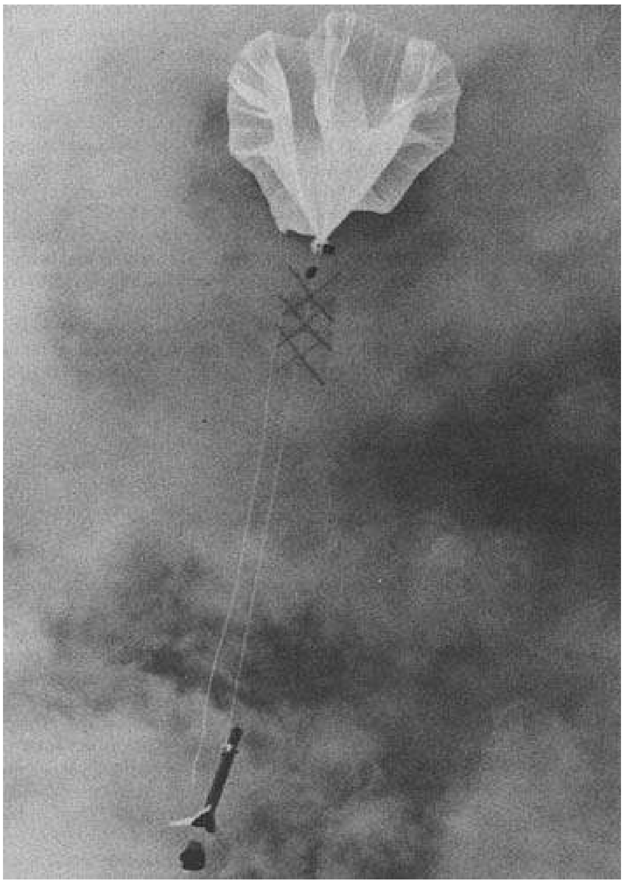

HIREGS attached to launch vehicle while balloon is inflated (1993)

Rockoons

The rockoon (a portmanteau of rocket and balloon) was a solid fuel rocket that, rather than being immediately lit while on the ground, was first carried into the upper atmosphere by a gas-filled balloon. Then, once separated from the balloon at its maximum height, the rocket was automatically ignited. This achieved a higher altitude, since the rocket did not have to move through the lower, thicker air layers.

The original concept of "rockoons" was developed by Cmdr. Lee Lewis, Cmdr. G. Halvorson, S. F. Singer, and James A. Van Allen during the Aerobee rocket firing cruise of the USS *Norton Sound* on March 1, 1949.[1]

From July 17 to July 27, 1956 the USA Naval Research Laboratory (NRL) shipboard launched 8 Deacon rockoons for solar ultraviolet and X-ray observations at ~30° N ~121.6° W, southwest of San Clemente Island, apogee: 120 km.[8]



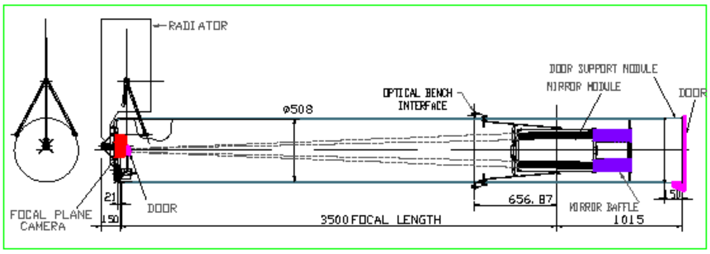
A Navy Deacon rockoon just after a shipboard launch, July 1956. The Deacon rocket is suspended below the balloon.

X-ray astronomy satellites

X-ray astronomy satellites study X-ray emissions from celestial objects. Satellites, which can detect and transmit data about the X-ray emissions are deployed as part of branch of space science known as X-ray astronomy. Satellites are needed because X-radiation is absorbed by the Earth's atmosphere, so instruments to detect X-rays must be taken to high altitude by balloons, sounding rockets, and satellites.

X-ray telescopes and mirrors

X-ray telescopes (XRTs) have varying directionality or imaging ability based on glancing angle reflection rather than refraction or large deviation reflection.[9] [10] This limits them to much narrow fields of view than visible or UV telescopes. The mirrors can be made of ceramic or metal foil.[11]



The Swift XRT contains a grazing incidence Wolter I telescope to focus X-rays onto a state-of-the-art CCD. The complete mirror module for the XRT consists of the X-ray mirrors, thermal baffle, a mirror collar, and an electron deflector. To prevent on-orbit degradation of the mirror module's performance, it is be maintained at 20 ± 5 °C, with gradients of <1 °C by an actively controlled thermal baffle (purple, in schematic below) similar to the one used for JET-X. A composite telescope tube holds the focal plane camera (red), containing a single CCD-22 detector.

The first X-ray telescope in astronomy was used to observe the Sun. The first X-ray picture of the Sun was taken in 1963, by a rocket-borne telescope.

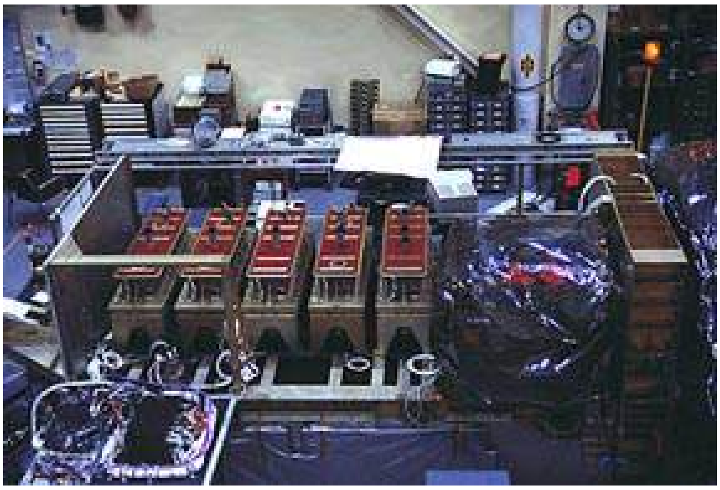
The utilization of X-ray mirrors for extrasolar X-ray astronomy simultaneously requires

- the ability to determine the location at the arrival of an X-ray photon in two dimensions and
- a reasonable detection efficiency.

X-ray astronomy detectors

X-ray astronomy detectors have been designed and configured primarily for energy and occasionally for wave-length detection using a variety of techniques usually limited to the technology of the time.

X-ray detectors collect individual X-rays (photons of X-ray electromagnetic radiation) including the number of photons collected (intensity), the energy (0.12 to 120 keV) of the photons collected, wavelength (~0.008 to 8 nm), or how fast the photons are detected (counts per hour), to tell us about the object that is emitting them.



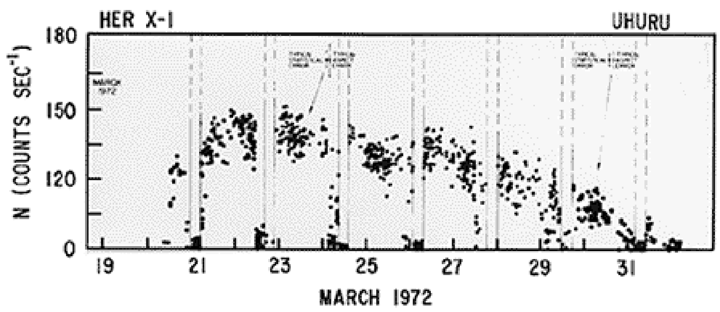
This is an image of the instrument called the Proportional Counter Array on the Rossi X-ray Timing Explorer (RXTE) satellite.

Astrophysical sources of X-rays

Several types of astrophysical objects emit X-rays, from galaxy clusters, through black holes in active galactic nuclei (AGN) to galactic objects such as supernova remnants, stars, and binary stars containing a white dwarf (cataclysmic variable stars and super soft X-ray sources), neutron star or black hole (X-ray binaries). Some solar system bodies emit X-rays, the most notable being the Moon, although most of the X-ray brightness of the Moon arises from reflected solar X-rays. A combination of many unresolved X-ray sources is thought to produce the observed X-ray background. The X-ray continuum can arise from bremsstrahlung, either magnetic or ordinary Coulomb, black-body radiation, synchrotron radiation, inverse Compton scattering of lower-energy photons be relativistic electrons, knock-on collisions of fast protons with atomic electrons, and atomic recombination, with or without additional electron transitions.[12]

An intermediate-mass X-ray binary (IMXB) is a binary star system where one of the components is a neutron star or a black hole. The other component is an intermediate mass star.[13]

Hercules X-1 is composed of a neutron star accreting matter from a normal star (HZ Her) probably due to Roche lobe overflow. X-1 is the prototype for the massive X-ray binaries although it falls on the borderline, ~2 $M_{\odot}$, between high- and low-mass X-ray binaries.[14]

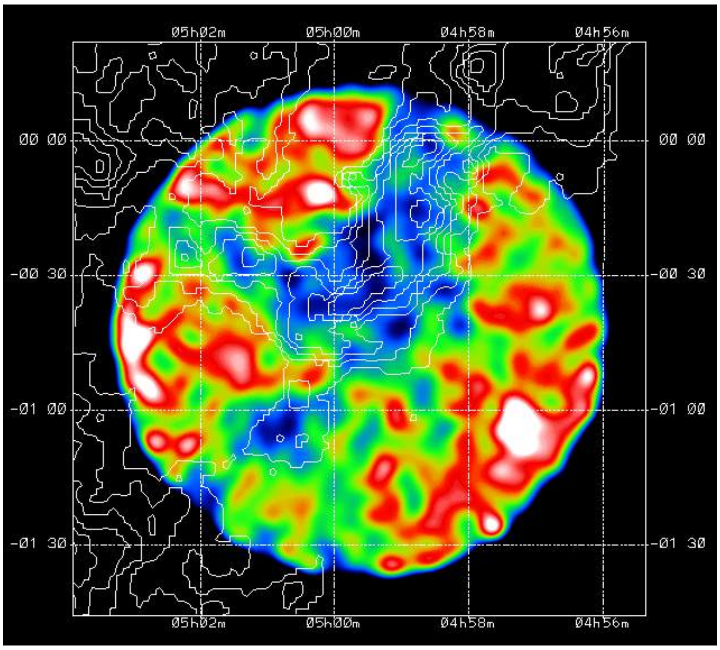


This light curve of Her X-1 shows long term and medium term variability. Each pair of vertical lines delineate the eclipse of the compact object behind its companion star. In this case, the companion is a 2 Solar-mass star with a radius of nearly 4 times that of our Sun. This eclipse shows us the orbital period of the system, 1.7 days.

Celestial X-ray sources

The celestial sphere has been divided into 88 constellations. The IAU constellations are areas of the sky. Each of these contains remarkable X-ray sources. Some of them are have been identified from astrophysical modeling to be galaxies or black holes at the centers of galaxies. Some are pulsars. As with sources already successfully modeled by X-ray astrophysics, striving to understand the generation of X-rays by the apparent source helps to understand the Sun, the universe as a whole, and how these affect us on Earth. Constellations are an astronomical device for handling observation and precision independent of current physical theory or interpretation. Astronomy has been around for a long time. Physical theory changes with time. With respect to celestial X-ray sources, X-ray astrophysics tends to focus on the physical reason for X-ray brightness, whereas X-ray astronomy tends to focus on their classification, order of discovery, variability, resolvability, and their relationship with nearby sources in other constellations.

Within the constellations Orion and Eridanus and stretching across them is a soft X-ray "hot spot" known as the **Orion-Eridanus Superbubble**, the **Eridanus Soft X-ray Enhancement**, or simply the **Eridanus Bubble**, a 25° area of interlocking arcs of Hα emitting filaments.



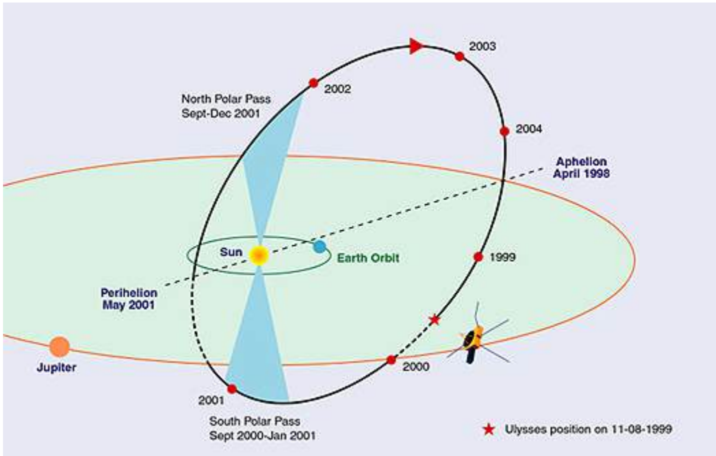
This ROSAT PSPC false-color image is of a portion of a nearby stellar wind superbubble (the **Orion-Eridanus Bubble**) stretching across Eridanus and Orion. Soft X-rays are emitted by hot gas (T ~ 2-3 MK) in the interior of the superbubble. This bright object forms the background for the "shadow" of a filament of gas and dust. The filament is shown by the overlaid contours, which represent 100 micrometre emission from dust at a temperature of about 30 K as measured by IRAS. Here the filament absorbs soft X-rays between 100 and 300 eV, indicating that the hot gas is located behind the filament. This filament may be part of a shell of neutral gas that surrounds the hot bubble. Its interior is energized by UV light and stellar winds from hot stars in the Orion OB1 association. These stars energize a superbubble about 1200 lys across which is observed in the optical (Hα) and X-ray portions of the spectrum.

Proposed (future) X-ray observatory satellites

There are several projects that are proposed for X-ray observatory satellites. See main article link above.

Explorational X-ray astronomy

Usually observational astronomy is considered to occur on Earth's surface (or beneath it in neutrino astronomy). The idea of limiting observation to Earth includes orbiting the Earth. As soon as the observer leaves the cozy confines of Earth, the observer becomes a deep space explorer.[15] Except for Explorer 1 and Explorer 3 and the earlier satellites in the series,[16] usually if it's going to be a deep space explorer it leaves the Earth or an orbit around the Earth.



Ulysses' second orbit: it arrived at Jupiter February 8, 1992 for a swing-by maneuver that increased its inclination to the ecliptic by 80.2 degrees.

For a satellite or space probe to qualify as a deep space X-ray astronomer/explorer or "astronobot"/explorer, all it needs to carry aboard is an XRT or X-ray detector and leave Earth orbit.

Ulysses was launched October 6, 1990, and reached Jupiter for its "gravitational slingshot" in February 1992. It passed the south solar pole in June 1994 and crossed the ecliptic equator in February 1995. The solar X-ray and cosmic gamma-ray burst experiment (GRB) had 3 main objectives: study and monitor solar flares, detect and localize cosmic gamma-ray bursts, and in-situ detection of Jovian aurorae. Ulysses was the first satellite carrying a gamma burst detector which went outside the orbit of Mars. The hard X-ray detectors operated in the range 15-150 keV. The detectors consisted of 23-mm thick × 51-mm diameter CsI(Tl) crystals mounted via plastic light tubes to photomultipliers. The hard detector changed its operating mode depending on (1) measured count rate, (2) ground command, or (3) change in spacecraft telemetry mode. The trigger level was generally set for 8-sigma above background and the sensitivity is 10^{-6} erg/cm^2 (1 nJ/m^2). When a burst trigger is recorded, the instrument switches to record high resolution data, recording it to a 32-kbit memory for a slow telemetry read out. Burst data consist of either 16 s of 8-ms resolution count rates or 64 s of 32-ms count rates from the sum of the 2 detectors. There were also 16 channel energy spectra from the sum of the 2 detectors (taken either in 1, 2, 4, 16, or 32 second integrations). During 'wait' mode, the data were taken either in 0.25 or 0.5 s integrations and 4 energy channels (with shortest integration time being 8 s). Again, the outputs of the 2 detectors were summed.

The Ulysses soft X-ray detectors consisted of 2.5-mm thick × 0.5 cm^2 area Si surface barrier detectors. A 100 mg/cm^2 beryllium foil front window rejected the low energy X-rays and defined a conical FOV of 75° (half-angle). These detectors were passively cooled and operate in the temperature range −35 to −55 °C. This detector had 6 energy channels, covering the range 5-20 keV.

Theoretical X-ray astronomy

Theoretical X-ray astronomy is a branch of theoretical astronomy that deals with the theoretical astrophysics and theoretical astrochemistry of X-ray generation, emission, and detection as applied to celestial objects.

Like theoretical astrophysics, theoretical X-ray astronomy uses a wide variety of tools which include analytical models (for example, polytropes to approximate the behaviors of a star) and computational numerical simulations. Once potential observational consequences are available they can be compared with experimental observations. Observers can look for data that refutes a model or helps in choosing between several alternate or conflicting models.

Theorists also try to generate or modify models to take into account new data. In the case of an inconsistency, the general tendency is to try to make minimal modifications to the model to fit the data. In some cases, a large amount of inconsistent data over time may lead to total abandonment of a model.

Most of the topics in astrophysics, astrochemistry, astrometry, and other fields that are branches of astronomy studied by theoreticians involve X-rays and X-ray sources. Many of the beginnings for a theory can be found in an Earth-based laboratory where an X-ray source is built and studied.

Dynamos

If some of the stellar magnetic fields are really induced by dynamos, then field strength might be associated with rotation rate.[17]

Astronomical models

From the observed X-ray spectrum, combined with spectral emission results for other wavelength ranges, an astronomical model addressing the likely source of X-ray emission can be constructed. For example, with Scorpius X-1 the X-ray spectrum steeply drops off as X-ray energy increases up to 20 keV, which is likely for a thermal-plasma mechanism.[12] In addition, there is no radio emission, and the visible continuum is roughly what would be expected from a hot plasma fitting the observed X-ray flux.[12] The plasma could be a corona to a central object or a transient plasma, where the energy source is unknown, but could be related to the idea of a close binary.[12]

In the Crab Nebula X-ray spectrum there are three features that differ greatly from Scorpius X-1: its spectrum is much harder, its source diameter is in ly, not AU, and its radio and optical synchrotron emission are strong.[12] Its overall X-ray luminosity rivals the optical emission and could be that of a nonthermal plasma. However, the Crab Nebula appears as an X-ray source that is a central freely expanding ball of dilute plasma, where the energy content is 100 times the total energy content of the large visible and radio portion, obtained from the unknown source.[12]

The "Dividing Line" as giant stars evolve to become red giants also coincides with the Wind and Coronal Dividing Lines.[18] To explain the drop in X-ray emission across these dividing lines, a number of models have been proposed:

1. low transition region densities, leading to low emission in coronae,
2. high-density wind extinction of coronal emission,
3. only cool coronal loops become stable,
4. change in magnetic field structure to an open topology, leading to a decrease of magnetically confined plasma,
5. change in magnetic dynamo character, leading to the disappearance of stellar fields leaving only small-scale, turbulence-generated fields among red giants.[18]

Analytical X-ray astronomy

High-mass X-ray binaries (HMXBs) are composed of an OB supergiant companion star and a compact object, usually a neutron star (NS) or black hole (BH). Supergiant X-ray binaries (SGXBs) are HMXBs in which the compact object orbits the massive companion within a few days (3-15 d) in circular (or slightly eccentric) orbits. SGXBs show typical hard X-ray spectra of accreting pulsars and most show a strong absorption as obscured HMXBs. X-ray luminosity increases up to 10^{36} erg·s^{-1} (10^{29} watts).

The mechanism triggering the different temporal behavior observed between the classical SGXBs and the recently discovered SFXTs is still debated.[19]

Aim: use the discovery of long orbits (>15 d) to help discriminate between emission models and perhaps bring constraints on the models.

Method: analyze archival data on various SGXBs such as has been obtained by INTEGRAL for candidates exhibiting long orbits. Build short- and long-term light curves. Perform a timing analysis in order to study the temporal behavior of each candidate on different time scales.

Compare various astronomical models:

- direct spherical accretion
- Roche-Lobe overflow via an accretion disk on the compact object.

Draw some conclusions: for example, the SGXB SAX J1818.6-1703 was discovered by BeppoSAX in 1998, identified as a SGXB of spectral type between O9I–B1I, which also displayed short and bright flares and an unusually very low quiescent level leading to its classification as a SFXT.[19] The analysis indicated an unusually long orbital period: 30.0 ± 0.2 d and an elapsed accretion phase of ~6 d implying an elliptical orbit and possible supergiant spectral type between B0.5-1I with eccentricities e ~ 0.3-0.4.[19] The large variations in the X-ray flux can be explained through accretion of macro-clumps formed within the stellar wind.[19]

Choose which model seems to work best: for SAX J1818.6-1703 the analysis best fits the model that predicts SFXTs behave as SGXBs with different orbital parameters; hence, different temporal behavior.[19]

Stellar X-ray astronomy

Stellar X-ray astronomy is said to have started on April 5, 1974, with the detection of X-rays from Capella.[20] A rocket flight on that date briefly calibrated its attitude control system when a star sensor pointed the payload axis at Capella (α Aur). During this period, X-rays in the range 0.2-1.6 keV were detected by an X-ray reflector system co-aligned with the star sensor.[20] The X-ray luminosity of 10^{31} erg·s^{-1} (10^{24} W) is four orders of magnitude above the Sun's X-ray luminosity.[20]

Eta Carinae


Classified as a Peculiar star, Eta Carinae exhibits a superstar at its center as seen in this image from Chandra. The new X-ray observation shows three distinct structures: an outer, horseshoe-shaped ring about 2 light years in diameter, a hot inner core about 3 light-months in diameter, and a hot central source less than 1 light-month in diameter which may contain the superstar that drives the whole show. The outer ring provides evidence of another large explosion that occurred over 1,000 years ago. Credit: Chandra Science Center and NASA.

Three structures around Eta Carinae are thought to represent shock waves produced by matter rushing away from the superstar at supersonic speeds. The temperature of the shock-heated gas ranges from 60 MK in the central regions to 3 MK on the horseshoe-shaped outer structure. "The Chandra image contains some puzzles for existing ideas of how a star can produce such hot and intense X-rays," says Prof. Kris Davidson of the University of Minnesota.[21] Davidson is principal investigator for the Eta Carina observations by Hubble. "In the most popular theory, X-rays are made by colliding gas streams from two stars so close together that they'd look like a point source to us. But what happens to gas streams that escape to farther distances? The extended hot stuff in the middle of the new image gives demanding new conditions for any theory to meet."[21]

Stellar coronae

Coronal stars are ubiquitous among the stars in the cool half of the Hertzsprung-Russell diagram.[22] Experiments with instruments aboard Skylab and Copernicus have been used to search for soft X-ray emission in the energy range ~0.14-0.284 keV from stellar coronae.[23] The experiments aboard ANS succeeded in finding X-ray signals from Capella and Sirius (α CMa). X-ray emission from an enhanced solar-like corona was proposed for the first time.[23] The high temperature of Capella's corona as obtained from the first coronal X-ray spectrum of Capella using HEAO 1 required magnetic confinement unless it was a free-flowing coronal wind.[22]

In 1977 Proxima Centauri was discovered to be emitting high-energy radiation in the XUV. In 1978, α Cen was identified as a low-activity coronal source.[24] With the operation of the Einstein observatory, X-ray emission was recognized as a characteristic feature common to a wide range of stars covering essentially the whole Hertzsprung-Russell diagram.[24] The Einstein initial survey led to significant insights:

- X-ray sources abound among all types of stars, across the Hertzsprung-Russell diagram and across most stages of evolution,
- the X-ray luminosities and their distribution along the main sequence were not in agreement with the long-favored acoustic heating theories, but were now interpreted as the effect of magnetic coronal heating, and
- stars that are otherwise similar reveal large differences in their X-ray output if their rotation period is different.[22]

To fit the medium-resolution spectrum of UX Ari, subsolar abundances were required.[22]

Stellar X-ray astronomy is contributing toward a deeper understanding of

- magnetic fields in magnetohydrodynamic dynamos,
- the release of energy in tenuous astrophysical plasmas through various plasma-physical processes, and
- the interactions of high-energy radiation with the stellar environment.[22]

Current wisdom has it that the massive coronal main sequence stars are late-A or early F stars, a conjecture that is supported both by observation and by theory.[22]

Unstable winds

Given the lack of a significant outer convection zone, theory predicts the absence of a magnetic dynamo in earlier A stars.[22] In early stars of spectral type O and B, shocks developing in unstable winds are the likely source of X-rays.[22]

Coolest M dwarfs

Beyond spectral type M5, the classical αω dynamo can no longer operate as the internal structure of dwarf stars changes significantly: they become fully convective.[22] As a distributed (or α^2) dynamo may become relevant, both the magnetic flux on the surface and the topology of the magnetic fields in the corona should systematically change across this transition, perhaps resulting in some discontinuities in the X-ray characteristics around spectral class dM5.[22] However, observations do not seem to support this picture: long-time lowest-mass X-ray detection, VB 8 (M7e V), has shown steady emission at levels of X-ray luminosity (L_X) ≈ 10^{26} erg·s^{-1} (10^{19} W) and flares up to an order of magnitude higher.[22] Comparison with other late M dwarfs shows a rather continuous trend.[22]

Strong X-ray emission from Herbig Ae/Be stars

Herbig Ae/Be stars are pre-main sequence stars. As to their X-ray emission properties, some are

- reminiscent of hot stars,
- others point to coronal activity as in cool stars, in particular the presence of flares and very high temperatures.[22]

The nature of these strong emissions has remained controversial with models including

- unstable stellar winds,
- colliding winds,
- magnetic coronae,
- disk coronae,
- wind-fed magnetospheres,
- accretion shocks,
- the operation of a shear dynamo,
- the presence of unknown late-type companions.[22]

K giants

The FK Com stars are giants of spectral type K with an unusually rapid rotation and signs of extreme activity. Their X-ray coronae are among the most luminous (L_X ≥ 10^{32} erg·s^{-1} or 10^{25} W) and the hottest known with dominant temperatures up to 40 MK.[22] However, the current popular hypothesis involves a merger of a close binary system in which the orbital angular momentum of the companion is transferred to the primary.[22]

Pollux is the brightest star in the constellation Gemini, despite its Beta designation, and the 17th brightest in the sky. Pollux is a giant orange K star that makes an interesting color contrast with its white "twin", Castor. Evidence has been found for a hot, outer, magnetically supported corona around Pollux, and the star is known to be an X-ray emitter.[25]

Amateur X-ray astronomy

Collectively, amateur astronomers observe a variety of celestial objects and phenomena sometimes with equipment that they build themselves. The United States Air Force Academy (USAFA) is the home of the US's only undergraduate satellite program, and has and continues to develop the FalconLaunch sounding rockets.[26] In addition to any direct amateur efforts to put X-ray astronomy payloads into space, there are opportunities that allow student-developed experimental payloads to be put on board commercial sounding rockets as a free-of-charge ride.[27]

There are major limitations to amateurs observing and reporting experiments in X-ray astronomy: the cost of building an amateur rocket or balloon to place a detector high enough and the cost of appropriate parts to build a suitable X-ray detector.

History of X-ray astronomy

In 1927, E.O. Hulburt of the US Naval Research Laboratory and associates Gregory Breit and Merle A. Tuve of the Carnegie Institution of Washington explored the possibility of equipping Robert H. Goddard's rockets to explore the upper atmosphere. "Two years later, he proposed an experimental program in which a rocket might be instrumented to explore the upper atmosphere, including detection of ultraviolet radiation and X-rays at high altitudes".[28]

In the late 1930s, the presence of a very hot, tenuous gas surrounding the Sun was inferred indirectly from optical coronal lines of highly ionized species.[22] The Sun has been known to be surrounded by a hot tenuous corona.[29] In the mid-1940s radio observations revealed a radio corona around the Sun.[22]

The beginning of the search for X-ray sources from above the Earth's atmosphere was on August 5, 1948 12:07 GMT. A US Army (formerly German) V-2 rocket as part of Project Hermes was launched from White Sands Proving Grounds. The first solar X-rays were recorded by T. Burnight.[30]

NRL scientists J. D. Purcell, C. Y. Johnson, and Dr. F. S. Johnson among those recovering instruments from a V-2 used for upper atmospheric research above the New Mexico desert. This is V-2 number 54, launched January 18, 1951 (photo by Dr. Richard Tousey, NRL).

Through the 1960s, 70s, 80s, and 90s, the sensitivity of detectors increased greatly during the 60 years of X-ray astronomy. In addition, the ability to focus X-rays has developed enormously—allowing the production of high-quality images of many fascinating celestial objects.

Major questions in X-ray astronomy

Stellar magnetic fields

Magnetic fields are ubiquitous among stars, yet we do not understand precisely why, nor have we fully understood the bewildering variety of plasma physical mechanisms that act in stellar environments.[22]

Extrasolar X-ray source astrometry

With the initial detection of an extrasolar X-ray source, the first question usually asked is "What is the source?" An extensive search is often made in other wavelengths such as visible or radio for possible coincident objects. Many of the verified X-ray locations still do not have readily discernible sources. X-ray astrometry becomes a serious concern that results in ever greater demands for finer angular resolution and spectral radiance.

There are inherent difficulties in making X-ray/optical, X-ray/radio, and X-ray/X-ray identifications based solely on positional coincidents, especially with handicaps in making identifications, such as the large uncertainties in positional determinants made from balloons and rockets, poor source separation in the crowded region toward the galactic center, source variability, and the multiplicity of source nomenclature.[31]

X-ray source counterparts to stars can be identified by calculating the angular separation between source centroids and position of the star. The maximum allowable separation is a compromise between a larger value to identify as many real matches as possible and a smaller value to minimize the probability of spurious matches. "An adopted matching criterion of 40" finds nearly all possible X-ray source matches while keeping the probability of any spurious matches in the sample to 3%."[32]

Solar X-ray astronomy

All of the detected X-ray sources at, around, or near the Sun are within or associated with the coronal cloud which is its outer atmosphere.

Coronal heating problem

In the area of solar X-ray astronomy, there is the coronal heating problem. The photosphere of the Sun has an effective temperature of 5,570 K[33] yet its corona has an average temperature of 1-2 × 10^6 K.[34] However, the hottest regions are 8-20 × 10^6 K.[34] The high temperature of the corona shows that it is heated by something other than direct heat conduction from the photosphere.[35]

It is thought that the energy necessary to heat the corona is provided by turbulent motion in the convection zone below the photosphere, and two main mechanisms have been proposed to explain coronal heating.[34] The first is wave heating, in which sound, gravitational or magnetohydrodynamic waves are produced by turbulence in the convection zone.[34] These waves travel upward and dissipate in the corona, depositing their energy in the ambient gas in the form of heat.[36] The other is magnetic heating, in which magnetic energy is continuously built up by photospheric motion and released through magnetic reconnection in the form of large solar flares and myriad similar but smaller events—nanoflares.[37]

Currently, it is unclear whether waves are an efficient heating mechanism. All waves except Alfvén waves have been found to dissipate or refract before reaching the corona.[38] In addition, Alfvén waves do not easily dissipate in the corona. Current research focus has therefore shifted towards flare heating mechanisms.[34]

Coronal mass ejection

A coronal mass ejection (CME) is an ejected plasma consisting primarily of electrons and protons (in addition to small quantities of heavier elements such as helium, oxygen, and iron), plus the entraining coronal closed magnetic field regions. Evolution of these closed magnetic structures in response to various photospheric motions over different time scales (convection, differential rotation, meridional circulation) somehow leads to the CME.[39] Small-scale energetic signatures such as plasma heating (observed as compact soft X-ray brightening) may be indicative of impending CMEs.

The soft X-ray sigmoid (an S-shaped intensity of soft X-rays) is an observational manifestation of the connection between coronal structure and CME production.[39] "Relating the sigmoids at X-ray (and other) wavelengths to magnetic structures and current systems in the solar atmosphere is the key to understanding their relationship to CMEs."[39]

The first detection of a Coronal mass ejection (CME) as such was made on December 1, 1971 by R. Tousey of the US Naval Research Laboratory using OSO 7.[40] Earlier observations of **coronal transients** or even phenomena observed visually during solar eclipses are now understood as essentially the same thing.

The largest geomagnetic perturbation, resulting presumably from a "prehistoric" CME, coincided with the first-observed solar flare, in 1859. The flare was observed visually by Richard Christopher Carrington and the geomagnetic storm was observed with the recording magnetograph at Kew Gardens. The same instrument recorded a **crotchet**, an instantaneous perturbation of the Earth's ionosphere by ionizing soft X-rays. This could not easily be understood at the time because it predated the discovery of X-rays (by Roentgen) and the recognition of the ionosphere (by Kennelly and Heaviside).

Exotic X-ray sources

A microquasar is a smaller cousin of a quasar that is a radio emitting X-ray binary, with an often resolvable pair of radio jets. LSI+61°303 is a periodic, radio-emitting binary system that is also the gamma-ray source, CG135+01. Observations are revealing a growing number of recurrent X-ray transients, characterized by short outbursts with very fast rise times (tens of minutes) and typical durations of a few hours that are associated with OB supergiants and hence define a new class of massive X-ray binaries: Supergiant Fast X-ray Transients (SFXTs). Observations made by Chandra indicate the presence of loops and rings in the hot X-ray emitting gas that surrounds Messier 87. A **magnetar** is a type of neutron star with an extremely powerful magnetic field, the decay of which powers the emission of copious amounts of high-energy electromagnetic radiation, particularly X-rays and gamma rays.

X-ray dark stars

During the solar cycle, as shown in the sequence of images of the Sun in X-rays, the Sun is almost X-ray dark, almost an X-ray variable. Betelgeuse, on the other hand, appears to be always X-ray dark. Hardly any X-rays are emitted by red giants. There is a rather abrupt onset of X-ray emission around spectral type A7-F0, with a large range of luminosities developing across spectral class F. Altair is spectral type A7V and Vega is A0V. Altair's total X-ray luminosity is at least an order of magnitude larger than the X-ray luminosity for Vega. The outer convection zone of early F stars is expected to be very shallow and absent in A-type dwarfs, yet the acoustic flux from the interior reaches a maximum for late A and early F stars provoking investigations of magnetic activity in A-type stars along three principal lines. Chemically peculiar stars of spectral type Bp or Ap are appreciable magnetic radio sources, most Bp/Ap stars remain undetected, and of those reported early on as producing X-rays only few of them can be identified as probably single stars. X-ray observations offer the possibility to detect (X-ray dark) planets as they eclipse part of the corona of their parent star while in transit. "Such methods are particularly promising for low-mass stars as a Jupiter-like planet could eclipse a rather significant coronal area."

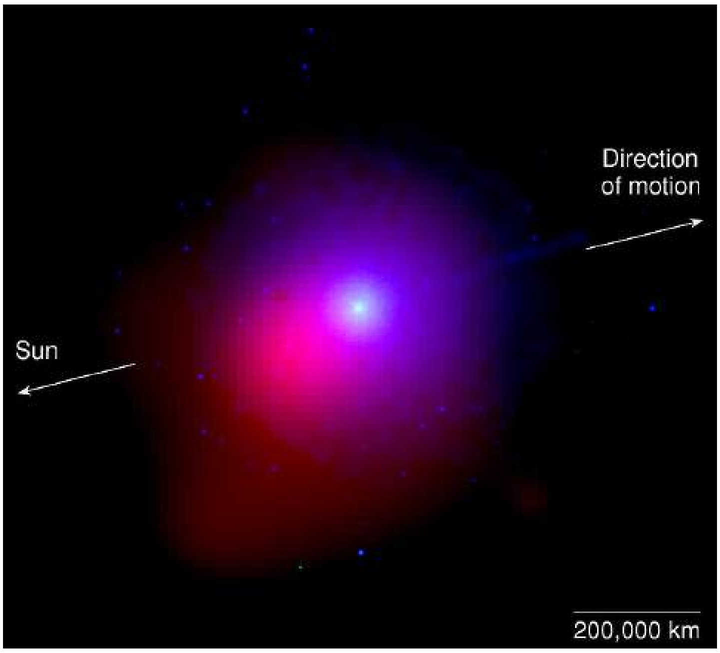
X-ray dark planet/comet

X-ray observations offer the possibility to detect (X-ray dark) planets as they eclipse part of the corona of their parent star while in transit. "Such methods are particularly promising for low-mass stars as a Jupiter-like planet could eclipse a rather significant coronal area."[22]

As X-ray detectors have become more sensitive, they have observed that some planets and other normally X-ray non-luminescent celestial objects under certain conditions emit, fluoresce, or reflect X-rays.

Comet Lulin

NASA's Swift Gamma-ray Explorer satellite was monitoring Comet Lulin as it closed to 63 Gm of Earth. For the first time, astronomers can see simultaneous UV and X-ray images of a comet. "The solar wind—a fast-moving stream of particles from the sun—interacts with the comet's broader cloud of atoms. This causes the solar wind to light up with X-rays, and that's what Swift's XRT sees", said Stefan Immler, of the Goddard Space Flight Center. This interaction, called charge exchange, results in X-rays from most comets when they pass within about three times Earth's distance from the sun. Because Lulin is so active, its atomic cloud is especially dense. As a result, the X-ray-emitting region extends far sunward of the comet.[41]



Comet Lulin was passing through the constellation Libra when Swift imaged it on January 28, 2009. This image merges data acquired by Swift's Ultraviolet/Optical Telescope (blue and green) and X-Ray Telescope (red). At the time of the observation, the comet was 99.5 million miles from Earth and 115.3 million miles from the Sun.

Single X-ray stars

In addition to the Sun there are many unary stars or star systems throughout the galaxy that emit X-rays. β Hydri (G2 IV) is a normal single, post main-sequence subgiant star, T_{eff} = 5800 K. It exhibits coronal X-ray fluxes.[42]

The benefit of studying single stars is that it allows measurements free of any effects of a companion or being a part of a multiple star system. Theories or models can be more readily tested. See, e.g., Betelgeuse, Red giants, and Vega and Altair.

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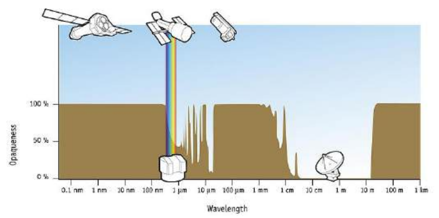
- X-ray all-sky survey on WIKISKY (http://www.wikisky.org/?object=Vela+Supernova+Remnant&img_source=RASS)
- Audio - Cain/Gay (2009) Astronomy Cast (http://www.astronomycast.com/astronomy/ep-135-x-ray-astronomy/) - X-Ray Astronomy

Gamma-ray astronomy

Gamma-ray astronomy is the astronomical study of the cosmos with gamma rays. Gamma-rays are the most energetic form of light that travel across the universe for incredible distances and have the smallest wavelength of any wave in the electromagnetic spectrum. Gamma-rays are created by and allow us to detect and observe celestial events such as supernova explosions, destruction of atoms, black holes and even the decay of radioactive material in space.[1]



Gamma rays are absorbed by the atmosphere and must be studied from a space telescope.

Early history

Compton Gamma Ray Observatory

Long before experiments could detect gamma rays emitted by cosmic sources, scientists had known that the universe should be producing these photons. Work by Eugene Feenberg and Henry Primakoff in 1948, Sachio Hayakawa and I.B. Hutchinson in 1952, and, especially, Philip Morrison in 1958[2] had led scientists to believe that a number of different processes which were occurring in the universe would result in gamma-ray emission. These processes included cosmic ray interactions with interstellar gas, supernova explosions, and interactions of energetic electrons with magnetic fields. However, it was not until the 1960s that our ability to actually detect these emissions came to pass.[3]

Most gamma rays coming from space are absorbed by the Earth's atmosphere, so gamma-ray astronomy could not develop until it was possible to get detectors above all or most of the atmosphere using balloons and spacecraft. The first gamma-ray telescope carried into orbit, on the Explorer 11 satellite in 1961, picked up fewer than 100 cosmic gamma-ray photons. They appeared to come from all directions in the Universe, implying some sort of uniform "gamma-ray background". Such a background would be expected from the interaction of cosmic rays (very energetic charged particles in space) with interstellar gas.

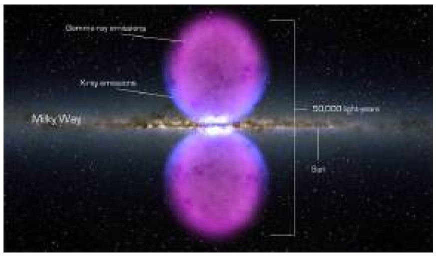
The first true astrophysical gamma-ray sources were solar flares, which revealed the strong 2.223 MeV line predicted by Morrison. This line results from the formation of deuterium via the union of a neutron and proton; in a solar flare the neutrons appear as secondaries from interactions of high-energy ions accelerated in the flare process. These first gamma-ray line observations were from OSO-3, OSO-7, and the Solar Maximum Mission, the latter spacecraft launched in 1980. The solar observations inspired theoretical work by Reuven Ramaty and others.[4]

Significant gamma-ray emission from our galaxy was first detected in 1967[5] by the detector aboard the OSO-3 satellite. It detected 621 events attributable to cosmic gamma rays. However, the field of gamma-ray astronomy took great leaps forward with the SAS-2 (1972) and the COS-B (1975–1982) satellites. These two satellites provided an exciting view into the high-energy universe (sometimes called the 'violent' universe, because the kinds of events in space that produce gamma rays tend to be high-speed collisions and similar processes). They confirmed the earlier findings of the gamma-ray background, produced the first detailed map of the sky at gamma-ray wavelengths, and detected a number of point sources. However the resolution of the instruments was insufficient to identify most of these point sources with specific visible stars or stellar systems.

Gamma-ray

A discovery in gamma-ray astronomy came in the late 1960s and early 1970s from a constellation of military defense satellites. Detectors on board the Vela satellite series, designed to detect flashes of gamma rays from nuclear bomb blasts, began to record bursts of gamma rays from deep space rather than the vicinity of the Earth. Later detectors determined that these gamma-ray bursts are seen to last for fractions of a second to minutes, appearing suddenly from unexpected directions, flickering, and then fading after briefly dominating the gamma-ray sky. Studied since the mid-1980s with instruments on board a variety of satellites and space probes, including Soviet Venera spacecraft and the Pioneer Venus Orbiter, the sources of these enigmatic high-energy flashes remain a mystery. They appear to come from far away in the Universe, and currently the most likely theory seems to be that at least some of them come from so-called *hypernova* explosions—supernovas creating black holes rather than neutron stars.

In November of 2010, using the Fermi Gamma-ray Space Telescope, two gigantic gamma-ray bubbles were detected at the heart of our galaxy. These bubbles appear as a mirror image[6] of each other. These bubbles of high-energy radiation are suspected as erupting from a massive black hole or evidence of a burst of star formations from millions of years ago.[7] These bubbles have been measured and span 25,000 light-years across. They were discovered after scientists filtered out the "fog of background gamma-rays suffusing the sky". This discovery confirmed previous clues that a large unknown "structure" was in the center of the Milky Way.[8] [9]



Two gigantic gamma-ray bubbles at the heart of the Milky Way.

Balloon flights

On June 19, 1988, from Birigüi (50° 20' W 21° 20' S) at 10:15 UTC a balloon launch occurred which carried two NaI(Tl) detectors (600 cm^2 total area) to an air pressure altitude of 5.5 mb for a total observation time of 6 hr.[10] The supernova SN1987A in the Large Magellanic Cloud (LMC) was discovered on February 23, 1987, and its progenitor is a blue supergiant (Sk -69 202) with luminosity of 2-5 x 10^{38} erg/s.[10] The 847 keV and 1238 keV gamma-ray lines from ^{56}Co decay have been detected.[10]

Solar flares

A solar flare is an explosion in a solar atmosphere and was originally detected visually in our own sun. Solar flares create massive amounts of radiation across the full electromagnetic spectrum from the longest wavelength, radio waves, to high energy gamma rays. The correlations of the high energy electrons energized during the flare and the gamma rays are mostly caused by nuclear combinations of high energy protons and other heavier ions. These gamma-rays can be observed and allow scientists to determine the major results of the energy released, which is not provided by the emissions from other wavelengths.[11] Nuclear gamma rays were observed from the solar flares of August 4 and 7, 1972, and November 22, 1977.[12]

Recent and current observatories

During its High Energy Astronomy Observatory program in 1977, NASA announced plans to build a "great observatory" for gamma-ray astronomy. The Compton Gamma-Ray Observatory (CGRO) was designed to take advantage of the major advances in detector technology during the 1980s, and was launched in 1991. The satellite carried four major instruments which have greatly improved the spatial and temporal resolution of gamma-ray observations. The CGRO provided large amounts of data which are being used to improve our understanding of the high-energy processes in our Universe. CGRO was de-orbited in June 2000 as a result of the failure of one of its stabilizing gyroscopes.

BeppoSAX was launched in 1996 and deorbited in 2003. It predominantly studied X-rays, but also observed gamma-ray bursts. By identifying the first non-gamma ray counterparts to gamma-ray bursts, it opened the way for their precise position determination and optical observation of their fading remnants in distant galaxies. The High Energy Transient Explorer 2 (HETE-2) was launched in October 2000 (on a nominally 2 yr mission) and was still operational in March 2007. Swift, a NASA spacecraft, was launched in 2004 and carries the BAT instrument for gamma-ray burst observations. Following BeppoSAX and HETE-2, it has observed numerous x-ray and optical counterparts to bursts, leading to distance determinations and detailed optical follow-up. These have established that most bursts originate in the explosions of massive stars (supernovas and hypernovas) in distant galaxies.

Currently the main space-based gamma-ray observatories are the INTErnational Gamma-Ray Astrophysics Laboratory, (INTEGRAL), and the Gamma-ray Large Area Space Telescope (GLAST). INTEGRAL is an ESA mission with additional contributions from Czech, Poland, USA and Russia. It was launched on 17 October 2002. NASA launched GLAST on 11 June 2008. In includes LAT, the Large Area Telescope, and GBM, the GLAST Burst Monitor, for studying gamma-ray bursts.

Very energetic gamma rays, with photon energies over ~30 GeV, can also be detected by ground based experiments. The extremely low photon fluxes at such high energies require detector effective areas that are impractically large for current space-based instruments. Fortunately such high-energy photons produce extensive showers of secondary particles in the atmosphere that can be observed on the ground, both directly by radiation counters and optically via the Cherenkov light the ultra-relativistic shower particles emit. The Imaging Atmospheric Cherenkov Telescope technique currently achieves the highest sensitivity. The Crab Nebula, a steady source of so called TeV gamma-rays, was first detected in 1989 by the Whipple Observatory at Mt. Hopkins, in Arizona in the USA. Modern Cherenkov telescope experiments like H.E.S.S., VERITAS, MAGIC, and CANGAROO III can detect the Crab Nebula in a few minutes. The most energetic photons (up to 16 TeV) observed from an extragalactic object originate from the blazar Markarian 501 (Mrk 501). These measurements were done by the High-Energy-Gamma-Ray Astronomy (HEGRA) air Cherenkov telescopes.

Gamma-ray astronomy observations are still limited by non-gamma ray backgrounds at lower energies, and, at higher energy, by the number of photons that can be detected. Larger area detectors and better background suppression are essential for progress in the field.[13]

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External links

- A History of Gamma-Ray Astronomy Including Related Discoveries (http://heasarc.gsfc.nasa.gov/docs/history/)
- The HEGRA Atmospheric Cherenkov Telescope System (http://www.mpi-hd.mpg.de/hfm/CT/CT.html)
- The HESS Ground Based Gamma-Ray Experiment (http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html)
- The MAGIC Telescope Project (http://magic.mppmu.mpg.de/)
- The VERITAS Ground Based Gamma-Ray Experiment (http://veritas.sao.arizona.edu/)
- The space-borne INTEGRAL observatory (http://integral.esac.esa.int/integral.html)
- NASA's Swift gamma-ray burst mission (http://swift.gsfc.nasa.gov/)
- The CACTUS Ground Based Air Cherenkov Telescope (http://ucdcms.ucdavis.edu/solar2/index.php)
- NASA HETE-2 satellite (http://heasarc.gsfc.nasa.gov/docs/hete2/hete2.html)
- TeGaSoCat (http://tegasocat.in2p3.fr), a TeV gamma-ray sources catalog.

Astrometry

Astrometry is the branch of astronomy that relates to precise measurements and explanations of the positions and movements of stars and other celestial bodies. Although once thought of as an esoteric field with little useful application for the future, the information obtained by astrometric measurements is now very important in contemporary research into the kinematics and physical origin of our Solar System and our Galaxy, the Milky Way.

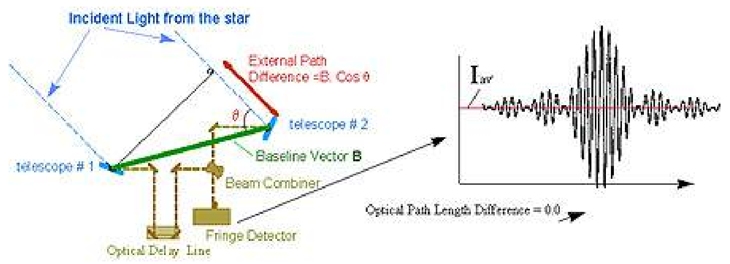


Illustration of the use of interferometry in the optical wavelength range to determine precise positions of stars. *Courtesy NASA/JPL-Caltech.*

History

The history of astrometry is linked to the history of star catalogues, which gave astronomers reference points for objects in the sky so they could track their movements. This can be dated back to Hipparchus, who around 190 BC used the catalogue of his predecessors Timocharis and Aristillus to discover the earth's precession. In doing so, he also developed the brightness scale still in use today.[1] Hipparchus compiled a catalogue with at least 850 stars and their positions.[2] Hipparchus's successor, Ptolemy, included a catalogue of 1,022 stars in his work the *Almagest*, giving their location, coordinates, and brightness.[3]

In the 10th century, Abd al-Rahman al-Sufi carried out observations on the stars and described their positions, magnitudes and star color, and gave drawings for each constellation, in his *Book of Fixed Stars*. Ibn Yunus observed more than 10,000 entries for the sun's position for many years using a large astrolabe with a diameter of nearly 1.4 metres. His observations on eclipses were still used centuries later in Simon Newcomb's investigations on the motion of the moon, while his other observations inspired Laplace's *Obliquity of the Ecliptic* and *Inequalities of Jupiter and Saturn*.[4] In the 15th century, the Timurid astronomer Ulugh Beg compiled the *Zij-i-Sultani*, in which he catalogued 1,019 stars. Like the earlier catalogs of Hipparchus and Ptolemy, Ulugh Beg's catalogue is estimated to have been precise to within approximately 20 minutes of arc.[5]

In the 16th century, Tycho Brahe used improved instruments, including large mural instruments, to measure star positions more accurately than previously, with a precision of 15–35 seconds.[6] Taqi al-Din measured the right ascension of the stars at the Istanbul observatory of Taqi al-Din using the "observational clock" he invented.[7] When telescopes became commonplace, setting circles sped measurements

James Bradley first tried to measure stellar parallaxes in 1729. The stellar movement proved too insignificant for his telescope, but he instead discovered the aberration of light and the nutation of the Earth's axis. His cataloguing of 3222 stars was refined in 1807 by Friedrich Bessel, the father of modern astrometry. He made the first measurement of stellar parallax: 0.3 arcsec for the binary star 61 Cygni.

Being very difficult to measure, only about 60 stellar parallaxes had been obtained by the end of the 19th century, mostly by use of the filar micrometer. Astrographs using astronomical photographic plates sped the process in the early 20th century. Automated plate-measuring machines[8] and more sophisticated computer technology of the 1960s allowed more efficient compilation of star catalogues. In the 1980s, charge-coupled devices (CCDs) replaced photographic plates and reduced optical uncertainties to one milliarcsecond. This technology made astrometry less expensive, opening the field to an amateur audience.

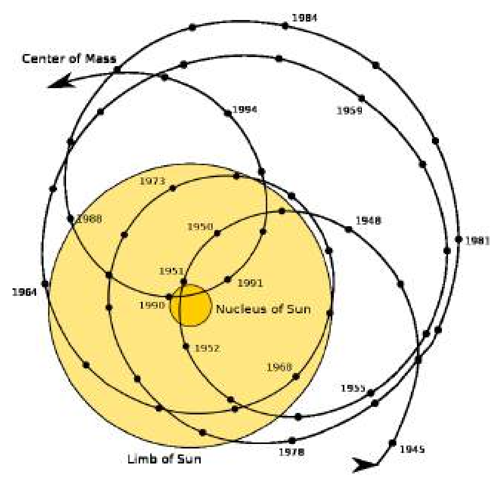
In 1989, the European Space Agency's Hipparcos satellite took astrometry into orbit, where it could be less affected by mechanical forces of the Earth and optical distortions from its atmosphere. Operated from 1989 to 1993, Hipparcos measured large and small angles on the sky with much greater precision than any previous optical telescopes. During its 4-year run, the positions, parallaxes, and proper motions of 118,218 stars were determined with an unprecedented degree of accuracy. A new “Tycho catalog” drew together a database of 1,058,332 to within 20-30 mas. Additional catalogues were compiled for the 23,882 double/multiple stars and 11,597 variable stars also analyzed during the Hipparcos mission.[9]

Today, the catalogue most often used is USNO-B1.0, an all-sky catalogue that tracks proper motions, positions, magnitudes and other characteristics for over one billion stellar objects. During the past 50 years, 7,435 Schmidt camera plates were used to complete several sky surveys that make the data in USNO-B1.0 accurate to within 0.2 arcsecond.[10]

Applications

Apart from the fundamental function of providing astronomers with a reference frame to report their observations in, astrometry is also fundamental for fields like celestial mechanics, stellar dynamics and galactic astronomy. In observational astronomy, astrometric techniques help identify stellar objects by their unique motions. It is instrumental for keeping time, in that UTC is basically the atomic time synchronized to Earth's rotation by means of exact observations. Astrometry is also involved in creating the cosmic distance ladder because it is used to establish parallax distance estimates for stars in the Milky Way.

Astrometry has also been used to support claims of extrasolar planet detection by measuring the displacement the proposed planets cause in their parent star's apparent position on the sky, due to their mutual orbit around the center of mass of the system. Although, as of 2009, none of the extrasolar planets detected by ground-based astrometry has been verified in subsequent studies, astrometry is expected to be more accurate in space missions that are not affected by the distorting effects of the Earth's atmosphere.[11] NASA's planned Space Interferometry Mission (SIM PlanetQuest) will utilize astrometric techniques to detect terrestrial planets orbiting 200 or so of the nearest solar-type stars, and the European Space Agency's GAIA (due to launch in 2012), which will be applying astrometric techniques in its stellar census.[12]



Motion of barycenter of solar system relative to the Sun.

Astrometric measurements are used by astrophysicists to constrain certain models in celestial mechanics. By measuring the velocities of pulsars, it is possible to put a limit on the asymmetry of supernova explosions. Also, astrometric results are used to determine the distribution of dark matter in the galaxy.

Astronomers use astrometric techniques for the tracking of near-Earth objects. Astrometry is responsible for the detection of many record-breaking solar system objects. To find such objects astrometrically, astronomers use telescopes to survey the sky and large-area cameras to take pictures at various determined intervals. By studying these images, they can detect solar system objects by their movements relative to the background stars, which remain fixed. Once a movement per unit time is observed, astronomers compensate for the amount of parallax caused by the earth’s motion during this time and the heliocentric distance to this object is calculated. Then, using this distance and other photographs, more information about the object, such as parallax, proper motion, and the semimajor axis of its orbit, can be obtained.[13]

50000 Quaoar and 90377 Sedna are two solar system objects discovered in this way by Michael E. Brown and others at Caltech using the Palomar Observatory’s Samuel Oschin telescope of 48 inches (1.2 m) and the Palomar-Quest large-area CCD camera. The ability of astronomers to track the positions and movements of such celestial bodies is crucial to the understanding of our Solar System and its interrelated past, present, and future with others in our Universe.[14] [15]

Statistics

A fundamental aspect of astrometry is error correction. Various factors introduce errors into the measurement of stellar positions, including atmospheric conditions, imperfections in the instruments and errors by the observer or the measuring instruments. Many of these errors can be reduced by various techniques, such as through instrument improvements and compensations to the data. The results are then analyzed using statistical methods to compute data estimates and error ranges.

Computer programs

- Astrometry.net [16]
- Astrometrica
- MPO (computer program)

In fiction

- In *Star Trek: Voyager*, the **Astrometrics** lab is the set for various scenes.
- In Battlestar Galactica (2004 TV series) an Astrometrics lab is stated in dialogue multiple times.

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External links

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- "Hall of Precision Astrometry" (http://www.astro.virginia.edu/~rjp0i/museum/engines.html). University of Virginia Department of Astronomy. Retrieved 2006-08-10.
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- http://www.space.com/scienceastronomy/quaoar_discovery_021007.html
- http://www.gps.caltech.edu/~mbrown Mike Brown's Caltech Home Page
- http://www.gps.caltech.edu/%7Embrown/papers/ps/sedna.pdf Scientific Paper describing Sedna's discovery
- http://www.rssd.esa.int/index.php?project=HIPPARCOS

Celestial mechanics

Celestial mechanics is the branch of astronomy that deals with the motions of celestial objects. The field applies principles of physics, historically classical mechanics, to astronomical objects such as stars and planets to produce ephemeris data. Orbital mechanics (astrodynamics) is a subfield which focuses on the orbits of artificial satellites. Lunar theory is another subfield focusing on the orbit of the Moon.

History of celestial mechanics

Modern analytic celestial mechanics started over 300 years ago with Isaac Newton's Principia of 1687. The name "celestial mechanics" is more recent than that. Newton wrote that the field should be called "rational mechanics." The term "dynamics" came in a little later with Gottfried Leibniz, and over a century after Newton, Pierre-Simon Laplace introduced the term "celestial mechanics." Nevertheless, prior studies addressing the problem of planetary positions are known going back perhaps 3,000 or more years, as early as the Babylonian astronomers.

Classical Greek writers speculated widely regarding celestial motions, and presented many geometrical mechanisms to model the motions of the planets. Their models employed combinations of uniform circular motion and were centered on the earth. An independent philosophical tradition was concerned with the physical causes of such circular motions. An extraordinary figure among the ancient Greek astronomers is Aristarchus of Samos (310 BC - c.230 BC), who suggested a heliocentric model of the universe and attempted to measure Earth's distance from the Sun.

The only known supporter of Aristarchus was Seleucus of Seleucia, a Babylonian astronomer who is said to have proved heliocentrism through reasoning in the 2nd century BC. This may have involved the phenomenon of tides,[1] which he correctly theorized to be caused by attraction to the Moon and notes that the height of the tides depends on the Moon's position relative to the Sun.[2] Alternatively, he may have determined the constants of a geometric model for the heliocentric theory and developed methods to compute planetary positions using this model, possibly using early trigonometric methods that were available in his time, much like Copernicus.[3]

Claudius Ptolemy

Claudius Ptolemy was an ancient astronomer and astrologer in early Imperial Roman times who wrote several books on astronomy. The most significant of these was the *Almagest*, which remained the most important book on predictive geometrical astronomy for some 1400 years. Ptolemy selected the best of the astronomical principles of his Greek predecessors, especially Hipparchus, and appears to have combined them either directly or indirectly with data and parameters obtained from the Babylonians. Although Ptolemy relied mainly on the work of Hipparchus, he introduced at least one idea, the equant, which appears to be his own, and which greatly improved the accuracy of the predicted positions of the planets. Although his model was extremely accurate, it relied solely on geometrical constructions rather than on physical causes; Ptolemy did not use celestial mechanics.

Early Middle Ages

B. L. van der Waerden has interpreted the planetary models developed by Aryabhata (476-550), an Indian astronomer,[4] [5] and Albumasar (787-886), a Persian astronomer, to be heliocentric models[6] but this view has been strongly disputed by others.[7] In the 9th century AD, the Persian physicist and astronomer, Ja'far Muhammad ibn Mūsā ibn Shākir, hypothesized that the heavenly bodies and celestial spheres are subject to the same laws of physics as Earth, unlike the ancients who believed that the celestial spheres followed their own set of physical laws different from that of Earth.[8] He also proposed that there is a force of attraction between heavenly bodies,[9] vaguely foreshadowing the law of gravity.[10]

Ibn al-Haytham

In the early 11th century, Ibn al-Haytham presented a development of Ptolemy's geocentric epicyclic models in terms of nested celestial spheres.[11] In chapters 15-16 of his *Book of Optics*, he also discovered that the celestial spheres do not consist of solid matter.[12]

Late Middle Ages

There was much debate on the dynamics of the celestial spheres during the late Middle Ages. Averroes (Ibn Rushd), Ibn Bajjah (Avempace) and Thomas Aquinas developed the theory of inertia in the celestial spheres, while Avicenna (Ibn Sina) and Jean Buridan developed the theory of impetus in the celestial spheres.

In the 14th century, Ibn al-Shatir produced the first model of lunar motion which matched physical observations, and which was later used by Copernicus.[13] In the 13th to 15th centuries, Tusi and Ali Kuşçu provided the earliest empirical evidence for the Earth's rotation, using the phenomena of comets to refute Ptolemy's claim that a stationary Earth can be determined through observation. Kuşçu further rejected Aristotelian physics and natural philosophy, allowing astronomy and physics to become empirical and mathematical instead of philosophical. In the early 16th century, the debate on the Earth's motion was continued by Al-Birjandi (d. 1528), who in his analysis of what might occur if the Earth were rotating, develops a hypothesis similar to Galileo Galilei's notion of "circular inertia", which he described in the following observational test:[14] [15]

> "The small or large rock will fall to the Earth along the path of a line that is perpendicular to the plane (*sath*) of the horizon; this is witnessed by experience (*tajriba*). And this perpendicular is away from the tangent point of the Earth’s sphere and the plane of the perceived (*hissi*) horizon. This point moves with the motion of the Earth and thus there will be no difference in place of fall of the two rocks."

Johannes Kepler

Johannes Kepler (December 27, 1571 - November 15, 1630) was the first to closely integrate the predictive geometrical astronomy, which had been dominant from Ptolemy to Copernicus, with physical concepts to produce a *New Astronomy, Based upon Causes, or Celestial Physics....* His work led to the modern laws of planetary orbits, which he developed using his physical principles and the planetary observations made by Tycho Brahe. Kepler's model greatly improved the accuracy of predictions of planetary motion, years before Isaac Newton developed his law of gravitation.

See Kepler's laws of planetary motion and the Keplerian problem for a detailed treatment of how his laws of planetary motion can be used.

Isaac Newton

Isaac Newton (January 4, 1643 – March 31, 1727) is credited with introducing the idea that the motion of objects in the heavens, such as planets, the Sun, and the Moon, and the motion of objects on the ground, like cannon balls and falling apples, could be described by the same set of physical laws. In this sense he unified *celestial* and *terrestrial* dynamics. Using Newton's law of universal gravitation, proving Kepler's Laws for the case of a circular orbit is simple. Elliptical orbits involve more complex calculations, which Newton included in his Principia.

Joseph-Louis Lagrange

After Newton, Lagrange (January 25, 1736 - April 10, 1813) attempted to solve the three-body problem, analyzed the stability of planetary orbits, and discovered the existence of the Lagrangian points. Lagrange also reformulated the principles of classical mechanics, emphasizing energy more than force and developing a method to use a single polar coordinate equation to describe any orbit, even those that are parabolic and hyperbolic. This is useful for calculating the behaviour of planets and comets and such. More recently, it has also become useful to calculate spacecraft trajectories.

Simon Newcomb

Simon Newcomb (March 12, 1835 – July 11, 1909) was a Canadian-American astronomer who revised Peter Andreas Hansen's table of lunar positions. In 1877, assisted by George William Hill, he recalculated all the major astronomical constants. After 1884, he conceived with A. M. W. Downing a plan to resolve much international confusion on the subject. By the time he attended a standardisation conference in Paris, France in May 1886, the international consensus was that all ephemerides should be based on Newcomb's calculations. A further conference as late as 1950 confirmed Newcomb's constants as the international standard.

Albert Einstein

Albert Einstein (March 14, 1879 – April 18, 1955) explained the anomalous precession of Mercury's perihelion in his 1916 paper *The Foundation of the General Theory of Relativity*. This led astronomers to recognize that Newtonian mechanics did not provide the highest accuracy. Binary pulsars have been observed, the first in 1974, whose orbits not only require the use of General Relativity for their explanation, but whose evolution proves the existence of gravitational radiation, a discovery that led to the 1993 Nobel Physics Prize.

Examples of problems

Celestial motion without additional forces such as thrust of a rocket, is governed by gravitational acceleration of masses due to other masses. A simplification is the *n*-body problem, where the problem assumes some number *n* of spherically symmetric masses. In that case, the integration of the accelerations can be well approximated by relatively simple summations.

Examples:

- 4-body problem: spaceflight to Mars (for parts of the flight the influence of one or two bodies is very small, so that there we have a 2- or 3-body problem; see also the patched conic approximation)
- 3-body problem:
  - Quasi-satellite
  - Spaceflight to, and stay at a Lagrangian point

In the case that *n*=2 (two-body problem), the situation is much simpler than for larger *n*. Various explicit formulas apply, where in the more general case typically only numerical solutions are possible. It is a useful simplification that is often approximately valid.

Examples:

- A binary star, e.g. Alpha Centauri (approx. the same mass)
- A binary asteroid, e.g. 90 Antiope (approx. the same mass)

A further simplification is based on the "standard assumptions in astrodynamics", which include that one body, the orbiting body, is much smaller than the other, the central body. This is also often approximately valid.

Examples:

- Solar system orbiting the center of the Milky Way
- A planet orbiting the Sun
- A moon orbiting a planet
- A spacecraft orbiting Earth, a moon, or a planet (in the latter cases the approximation only applies after arrival at that orbit)

Either instead of, or on top of the previous simplification, we may assume circular orbits, making distance and orbital speeds, and potential and kinetic energies constant in time. This assumption sacrifices accuracy for simplicity, especially for high eccentricity orbits which are by definition non-circular.

Examples:

- The orbit of the dwarf planet Pluto, ecc. = 0.2488
- The orbit of Mercury, ecc. = 0.2056
- Hohmann transfer orbit
- Gemini 11 flight
- Suborbital flights

Perturbation theory

Perturbation theory comprises mathematical methods that are used to find an approximate solution to a problem which cannot be solved exactly. (It is closely related to methods used in numerical analysis, which are ancient.) The earliest use of perturbation theory was to deal with the otherwise unsolveable mathematical problems of celestial mechanics: Newton's solution for the orbit of the Moon, which moves noticeably differently from a simple Keplerian ellipse because of the competing gravitation of the Earth and the Sun.

Perturbation methods start with a simplified form of the original problem, which carefully chosen to be exactly solvable. In celestial mechanics, this is usually a Keplerian ellipse, which is correct when there are only two gravitating bodies (say, the Earth and the Moon), or a circular orbit, which is only correct in special cases of two-body motion, but is often close enough for practical use. The solved, but simplified problem is then *"perturbed"* to make its starting conditions closer to the real problem, such as including the gravitational attraction of a third body (the Sun). The slight changes that result, which themselves may have been simplifed yet again, are used as corrections. Because of simplifications introduced along every step of the way, the corrections are never perfect, but even one cycle of corrections often provides a remarkably better approximate solution to the real problem.

There is no requirement to stop at only one cycle of corrections. A partially corrected solution can be re-used as the new starting point for yet another cycle of perturbations and corrections. The common difficulty with the method is that usually the corrections progressively make the new solutions very much more complicated, so each cycle is much more difficult to manage than the previous cycle of corrections. Newton is reported to have said, regarding the problem of the Moon's orbit *"It causeth my head to ache."*

This general procedure — starting with a simplified problem and gradually adding corrections that make the starting point of the corrected problem closer to the real situation — is a widely used mathematical tool in advanced sciences and engineering. It is the natural extension of the "guess, check, and fix" method used anciently with numbers.

Notes

[1] Lucio Russo, *Flussi e riflussi*, Feltrinelli, Milano, 2003, ISBN 88-07-10349-4.

[2] Bartel Leendert van der Waerden (1987). "The Heliocentric System in Greek, Persian and Hindu Astronomy", *Annals of the New York Academy of Sciences* **500** (1), 525–545 [527].

[3] Bartel Leendert van der Waerden (1987). "The Heliocentric System in Greek, Persian and Hindu Astronomy", *Annals of the New York Academy of Sciences* **500** (1), 525–545 [527-529].

[4] B. L. van der Waerden (1970), *Das heliozentrische System in der griechischen,persischen und indischen Astronomie,* Naturforschenden Gesellschaft in Zürich, Zürich: Kommissionsverlag Leeman AG. (cf. Noel Swerdlow (June 1973), "Review: A Lost Monument of Indian Astronomy", *Isis* **64** (2), p. 239-243.)
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> "Not only did Aryabhata believe that the earth rotates, but there are glimmerings in his system (and other similar systems) of a possible underlying theory in which the earth (and the planets) orbits the sun, rather than the sun orbiting the earth. The evidence is that the basic planetary periods are relative to the sun."

[6] Bartel Leendert van der Waerden (1987). "The Heliocentric System in Greek, Persian and Hindu Astronomy", *Annals of the New York Academy of Sciences* **500** (1), 525–545 [534-537].

[7] Noel Swerdlow (June 1973), "Review: A Lost Monument of Indian Astronomy" [review of B. L. van der Waerden, *Das heliozentrische System in der griechischen, persischen und indischen Astronomie*], *Isis* **64** (2), p. 239–243. David Pingree (1973), "The Greek Influence on Early Islamic Mathematical Astronomy", *Journal of the American Oriental Society* **93** (1), p. 32. Dennis Duke (2005), "The Equant in India: The Mathematical Basis of Ancient Indian Planetary Models", *Archive for History of Exact Sciences* **59**, p. 563–576 (http://people.scs.fsu.edu/~dduke/india8.pdf).

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[13] George Saliba (2007), Lecture at SOAS, London - Part 4/7 (http://youtube.com/watch?v=GfissgPCgfM) and Lecture at SOAS, London - Part 5/7 (http://youtube.com/watch?v=0VMBRAd6YBU)

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[15] Ragep, F. Jamil (2001b), "Freeing Astronomy from Philosophy: An Aspect of Islamic Influence on Science", *Osiris, 2nd Series* **16** (Science in Theistic Contexts: Cognitive Dimensions): 49–64 & 66–71

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Research

- Marshall Hampton's research page: Central configurations in the n-body problem (http://www.math.washington.edu/~hampton/research.html)

Artwork

- Celestial Mechanics is a Planetarium Artwork created by D. S. Hessels and G. Dunne (http://www.cmlab.com)

Course notes

- Professor Tatum's course notes at the University of Victoria (http://orca.phys.uvic.ca/~tatum/celmechs.html)

Associations

- Italian Celestial Mechanics and Astrodynamics Association (http://www.mat.uniroma2.it/simca/english.html)

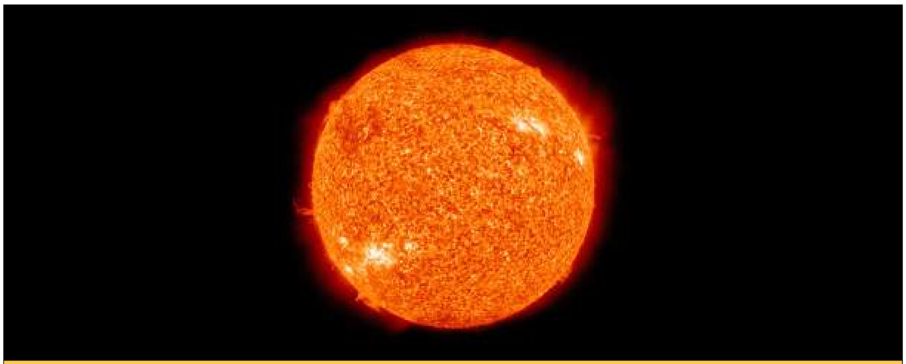
Simulations

- Online Celestial Mechanic Simulation (http://orinetz.com/planet/animatesystem.php?sysid=QUQTS2CSDQ44FDURR3XD6NUD6&orinetz_lang=1)

Specific subfields of astronomy

Sun

The Sun ☉



Observation data	
Mean distance from Earth	1.496×10^8 km 8 min 19 s at light speed
Visual brightness (*V*)	−26.74 [1]
Absolute magnitude	4.83 [1]
Spectral classification	G2V
Metallicity	*Z* = 0.0122[2]
Angular size	31.6′ – 32.7′ [3]
Adjectives	solar
Orbital characteristics	
Mean distance from Milky Way core	~2.5×10^{17} km 26000 light-years
Galactic period	$(2.25–2.50)\times10^8$ a
Velocity	~220 km/s (orbit around the center of the Galaxy) ~20 km/s (relative to average velocity of other stars in stellar neighborhood) ~370 km/s[4] (relative to the cosmic microwave background)
Physical characteristics	
Mean diameter	1.392×10^6 km [1] 109 × Earth
Equatorial radius	6.955×10^5 km [5] 109 × Earth[5]
Equatorial circumference	4.379×10^6 km [5] 109 × Earth[5]

Flattening	9×10^{-6}
Surface area	6.0877×10^{12} km^2 [5] 11990 × Earth[5]
Volume	1.412×10^{18} km^3 [5] 1300000 × Earth
Mass	1.9891×10^{30} kg[1] 333000 × Earth[1]
Average density	1.408×10^3 kg/m^3 [1] [5] [6]
Density	Center (model): 1.622×10^5 kg/m^3 [1] Lower photosphere: 2×10^{-4} kg/m^3 Lower chromosphere: 5×10^{-6} kg/m^3 Corona (avg.): 1×10^{-12} kg/m^3 [7]
Equatorial surface gravity	274.0 m/s^2 [1] 27.94 *g* 28 × Earth[5]
Escape velocity (from the surface)	617.7 km/s [5] 55 × Earth[5]
Temperature	Center (modeled): ~1.57×10^7 K [1] Photosphere (effective): 5778 K [1] Corona: ~5×10^6 K
Luminosity (L_{sol})	3.846×10^{26} W [1] ~3.75×10^{28} lm ~98 lm/W efficacy
Mean Intensity (I_{sol})	2.009×10^7 W·m^{-2}·sr^{-1}
Rotation characteristics	
Obliquity	7.25° [1] (to the ecliptic) 67.23° (to the galactic plane)
Right ascension of North pole[8]	286.13° 19h 4min 30s
Declination of North pole	+63.87° 63°52' North
Sidereal rotation period (at equator)	25.05 days [1]
(at 16° latitude)	25.38 days [1] 25d 9h 7min 12s [8]
(at poles)	34.4 days [1]
Rotation velocity (at equator)	7.189×10^3 km/h [5]
Photospheric composition (by mass)	
Hydrogen	73.46%[9]
Helium	24.85%

Oxygen	0.77%
Carbon	0.29%
Iron	0.16%
Neon	0.12%
Nitrogen	0.09%
Silicon	0.07%
Magnesium	0.05%
Sulfur	0.04%

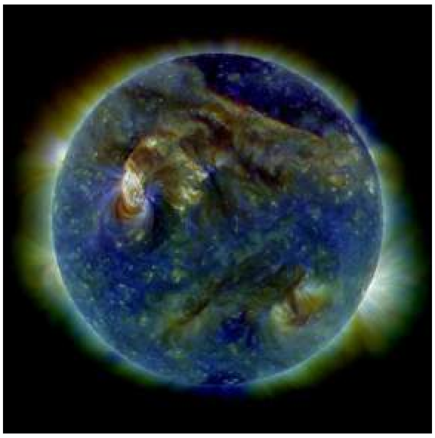
The **Sun** is the star at the center of the Solar System. It is almost perfectly spherical and consists of hot plasma interwoven with magnetic fields.[10] [11] It has a diameter of about 1,392,000 km, about 109 times that of Earth, and its mass (about 2×10^{30} kilograms, 330,000 times that of Earth) accounts for about 99.86% of the total mass of the Solar System.[12] Chemically, about three quarters of the Sun's mass consists of hydrogen, while the rest is mostly helium. Less than 2% consists of heavier elements, including oxygen, carbon, neon, iron, and others.[13]

The Sun's stellar classification, based on spectral class, is G2V, and is informally designated as a *yellow dwarf*, because its visible radiation is most intense in the yellow-green portion of the spectrum and although its color is white, from the surface of the Earth it may appear yellow because of atmospheric scattering of blue light.[14] [15] In the spectral class label, *G2* indicates its surface temperature of approximately 5778 K (5505 °C), and *V* indicates that the Sun, like most stars, is a main sequence star, and thus generates its energy by nuclear fusion of hydrogen nuclei into helium. In its core, the Sun fuses 620 million metric tons of hydrogen each second. Once regarded by astronomers as a small and relatively insignificant star, the Sun is now thought to be brighter than about 85% of the stars in the Milky Way galaxy, most of which are red dwarfs.[16] [17] The absolute magnitude of the Sun is +4.83; however, as the star closest to Earth, the Sun is the brightest object in the sky with an apparent magnitude of −26.74.[18] [19] The Sun's hot corona continuously expands in space creating the solar wind, a stream of charged particles that extends to the heliopause at roughly 100 astronomical units. The bubble in the interstellar medium formed by the solar wind, the heliosphere, is the largest continuous structure in the Solar System.[20] [21]

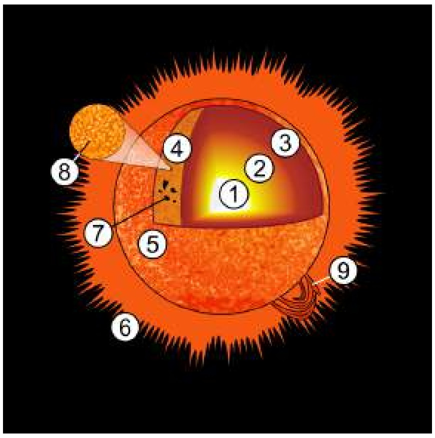
The Sun is currently traveling through the Local Interstellar Cloud in the Local Bubble zone, within the inner rim of the Orion Arm of the Milky Way galaxy. Of the 50 nearest stellar systems within 17 light-years from Earth (the closest being a red dwarf named Proxima Centauri at approximately 4.2 light years away), the Sun ranks 4th in mass.[22] The Sun orbits the center of the Milky Way at a distance of approximately 24000–26000 light years from the galactic center, completing one clockwise orbit, as viewed from the galactic north pole, in about 225–250 million years. Since our galaxy is moving with respect to the cosmic microwave background radiation (CMB) in the direction of constellation Hydra with a speed of 550 km/s, the sun's resultant velocity with respect to the CMB is about 370 km/s in the direction of Crater or Leo.[23]

The mean distance of the Sun from the Earth is approximately 149.6 million kilometers (1 AU), though the distance varies as the Earth moves from perihelion in January to aphelion in July.[24] At this average distance, light travels from the Sun to Earth in about 8 minutes and 19 seconds. The energy of this sunlight supports almost all life on Earth by photosynthesis,[25] and drives Earth's climate and weather. The enormous effect of the Sun on the Earth has been recognized since prehistoric times, and the Sun has been regarded by some cultures as a deity. An accurate scientific understanding of the Sun developed slowly, and as recently as the 19th century prominent scientists had little knowledge of the Sun's physical composition and source of energy. This understanding is still developing; there are a number of present-day anomalies in the Sun's behavior that remain unexplained.

Characteristics



The sun shows a C3-class solar flare (white area on upper left), a solar tsunami (wave-like structure, upper right) and multiple filaments of magnetism lifting off the stellar surface.



An illustration of the structure of the Sun:
1. Core
2. Radiative zone
3. Convective zone
4. Photosphere
5. Chromosphere
6. Corona
7. Sunspot
8. Granules
9. Prominence

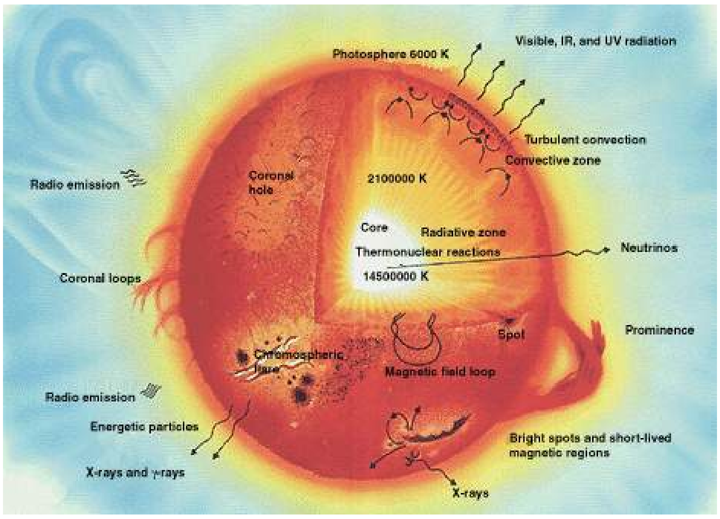
The Sun is a G-type main sequence star comprising about 99.8632% of the total mass of the Solar System. It is a near-perfect sphere, with an oblateness estimated at about 9 millionths,[26] which means that its polar diameter differs from its equatorial diameter by only 10 km. As the Sun consists of a plasma and is not solid, it rotates faster at its equator than at its poles. This behavior is known as differential rotation, and is caused by convection in the Sun and the movement of mass, due to steep temperature gradients from the core outwards. This mass carries a portion of the Sun’s counter-clockwise angular momentum, as viewed from the ecliptic north pole, thus redistributing the angular velocity. The period of this *actual rotation* is approximately 25.6 days at the equator and 33.5 days at the poles. However, due to our constantly changing vantage point from the Earth as it orbits the Sun, the *apparent rotation* of the star at its equator is about 28 days.[27] The centrifugal effect of this slow rotation is 18 million times weaker than the surface gravity at the Sun's equator. The tidal effect of the planets is even weaker, and does not significantly affect the shape of the Sun.[28]

The Sun is a Population I, or heavy element-rich,[29] star.[30] The formation of the Sun may have been triggered by shockwaves from one or more nearby supernovae.[31] This is suggested by a high abundance of heavy elements in the Solar System, such as gold and uranium, relative to the abundances of these elements in so-called Population II (heavy element-poor) stars. These elements could most plausibly have been produced by endergonic nuclear reactions during a supernova, or by transmutation through neutron absorption inside a massive second-generation star.[30]

The Sun does not have a definite boundary as rocky planets do, and in its outer parts the density of its gases drops exponentially with increasing distance from its center.[32] Nevertheless, it has a well-defined interior structure, described below. The Sun's radius is measured from its center to the edge of the photosphere. This is simply the layer above which the gases are too cool or too thin to radiate a significant amount of light, and is therefore the surface most readily visible to the naked eye.[27]

The solar interior is not directly observable, and the Sun itself is opaque to electromagnetic radiation. However, just as seismology uses waves generated by earthquakes to reveal the interior structure of the Earth, the discipline of helioseismology makes use of pressure waves (infrasound) traversing the Sun's interior to measure and visualize the star's inner structure.[27] Computer modeling of the Sun is also used as a theoretical tool to investigate its deeper layers.

Core



Cross-section of a solar-type star (NASA)

The core of the Sun is considered to extend from the center to about 20–25% of the solar radius.[33] It has a density of up to 150 g/cm^3[34] [35] (about 150 times the density of water) and a temperature of close to 13.6 million kelvin (K). By contrast, the Sun's surface temperature is approximately 5,800 K. Recent analysis of SOHO mission data favors a faster rotation rate in the core than in the rest of the radiative zone.[33] Through most of the Sun's life, energy is produced by nuclear fusion through a series of steps called the p–p (proton–proton) chain; this process converts hydrogen into helium.[36] Less than 2% of the helium generated in the Sun comes from the CNO cycle.

The core is the only region in the Sun that produces an appreciable amount of thermal energy through fusion; inside 24% of the Sun's radius, 99% of the power has been generated, and by 30% of the radius, fusion has stopped nearly entirely. The rest of the star is heated by energy that is transferred outward from the core and the layers just outside. The energy produced by fusion in the core must then travel through many successive layers to the solar photosphere before it escapes into space as sunlight or kinetic energy of particles.[32] [27]

The proton–proton chain occurs around 9.2×10^{37} times each second in the core of the Sun. Since this reaction uses four free protons (hydrogen nuclei), it converts about 3.7×10^{38} protons to alpha particles (helium nuclei) every second (out of a total of ~8.9×10^{56} free protons in the Sun), or about 6.2×10^{11} kg per second.[27] Since fusing hydrogen into helium releases around 0.7% of the fused mass as energy,[37] the Sun releases energy at the mass-energy conversion rate of 4.26 million metric tons per second, 384.6 yotta watts (3.846×10^{26} W),[1] or 9.192×10^{10} megatons of TNT per second. This mass is not destroyed to create the energy, rather, the mass is carried away *in* the radiated energy, as described by the concept of mass-energy equivalence.

The power production by fusion in the core varies with distance from the solar center. At the center of the Sun, theoretical models estimate it to be approximately 276.5 watts/m^3,[38] a power production density that more nearly approximates reptile metabolism than a thermonuclear bomb.[39] Peak power production in the Sun has been compared to the volumetric heats generated in an active compost heap. The tremendous power output of the Sun is not due to its high power per volume, but instead due to its large size.

The fusion rate in the core is in a self-correcting equilibrium: a slightly higher rate of fusion would cause the core to heat up more and expand slightly against the weight of the outer layers, reducing the fusion rate and correcting the perturbation; and a slightly lower rate would cause the core to cool and shrink slightly, increasing the fusion rate and again reverting it to its present level.[40] [41]

The gamma rays (high-energy photons) released in fusion reactions are absorbed in only a few millimeters of solar plasma and then re-emitted again in random direction and at slightly lower energy. Therefore it takes a long time for radiation to reach the Sun's surface. Estimates of the photon travel time range between 10,000 and 170,000 years.[42]

After a final trip through the convective outer layer to the transparent surface of the photosphere, the photons escape as visible light. Each gamma ray in the Sun's core is converted into several million photons of visible light before escaping into space. Neutrinos are also released by the fusion reactions in the core, but unlike photons they rarely interact with matter, so almost all are able to escape the Sun immediately. For many years measurements of the number of neutrinos produced in the Sun were lower than theories predicted by a factor of 3. This discrepancy was resolved in 2001 through the discovery of the effects of neutrino oscillation: the Sun emits the number of neutrinos predicted by the theory, but neutrino detectors were missing $^2/_3$ of them because the neutrinos had changed flavor by the time they were detected.[43]

Radiative zone

From about 0.25 to about 0.7 solar radii, solar material is hot and dense enough that thermal radiation is sufficient to transfer the intense heat of the core outward.[44] This zone is free of thermal convection; while the material gets cooler from 7 to about 2 million kelvin with increasing altitude, this temperature gradient is less than the value of the adiabatic lapse rate and hence cannot drive convection.[35] Energy is transferred by radiation—ions of hydrogen and helium emit photons, which travel only a brief distance before being reabsorbed by other ions.[44] The density drops a hundredfold (from 20 g/cm^3 to only 0.2 g/cm^3) from the bottom to the top of the radiative zone.[44]

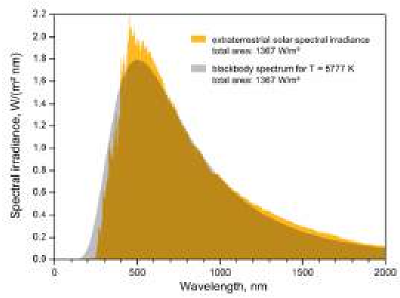
The radiative zone and the convection form a transition layer, the tachocline. This is a region where the sharp regime change between the uniform rotation of the radiative zone and the differential rotation of the convection zone results in a large shear—a condition where successive horizontal layers slide past one another.[45] The fluid motions found in the convection zone above, slowly disappear from the top of this layer to its bottom, matching the calm characteristics of the radiative zone on the bottom. Presently, it is hypothesized (see Solar dynamo), that a magnetic dynamo within this layer generates the Sun's magnetic field.[35]

Convective zone

In the Sun's outer layer, from its surface down to approximately 200,000 km (or 70% of the solar radius), the solar plasma is not dense enough or hot enough to transfer the thermal energy of the interior outward through radiation; in other words it is opaque enough. As a result, thermal convection occurs as thermal columns carry hot material to the surface (photosphere) of the Sun. Once the material cools off at the surface, it plunges downward to the base of the convection zone, to receive more heat from the top of the radiative zone. At the visible surface of the Sun, the temperature has dropped to 5,700 K and the density to only 0.2 g/m^3 (about 1/6,000th the density of air at sea level).[35]

The thermal columns in the convection zone form an imprint on the surface of the Sun as the solar granulation and supergranulation. The turbulent convection of this outer part of the solar interior causes a "small-scale" dynamo that produces magnetic north and south poles all over the surface of the Sun.[35] The Sun's thermal columns are Bénard cells and therefore tend to be hexagonal prisms.[46]

Photosphere

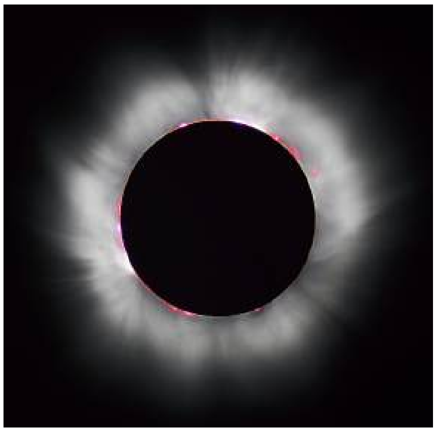


The effective temperature, or black body temperature, of the Sun (5777 K) is the temperature a black body of the same size must have to yield the same total emissive power.

The visible surface of the Sun, the photosphere, is the layer below which the Sun becomes opaque to visible light.[47] Above the photosphere visible sunlight is free to propagate into space, and its energy escapes the Sun entirely. The change in opacity is due to the decreasing amount of H^- ions, which absorb visible light easily.[47] Conversely, the visible light we see is produced as electrons react with hydrogen atoms to produce H^- ions.[48] [49] The photosphere is tens to hundreds of kilometers thick, being slightly less opaque than air on Earth. Because the upper part of the photosphere is cooler than the lower part, an image of the Sun appears brighter in the center than on the edge or *limb* of the solar disk, in a phenomenon known as limb darkening.[47] Sunlight has approximately a black-body spectrum that indicates its temperature is about 6,000 K, interspersed with atomic absorption lines from the tenuous layers above the photosphere. The photosphere has a particle density of ~10^{23} m^{-3} (this is about 0.37% of the particle number per volume of Earth's atmosphere at sea level; however, photosphere particles are electrons and protons, so the average particle in air is 58 times as heavy).[44]

During early studies of the optical spectrum of the photosphere, some absorption lines were found that did not correspond to any chemical elements then known on Earth. In 1868, Norman Lockyer hypothesized that these absorption lines were because of a new element which he dubbed *helium*, after the Greek Sun god Helios. It was not until 25 years later that helium was isolated on Earth.[50]

Atmosphere

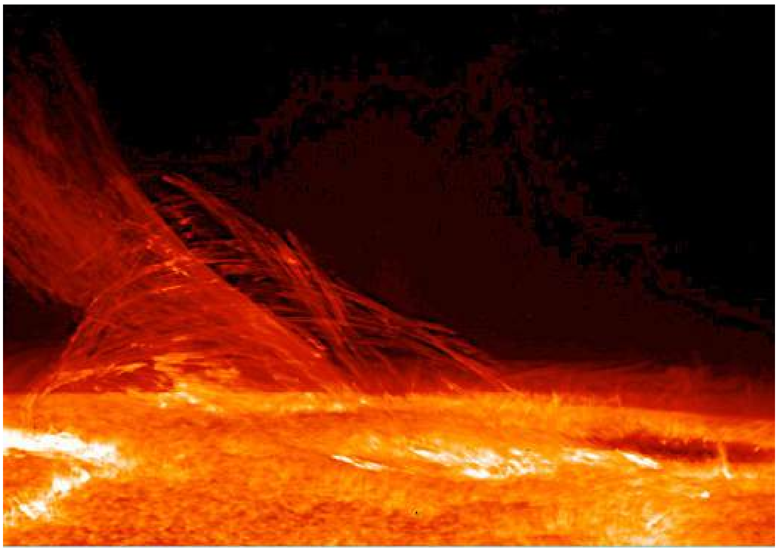


During a total solar eclipse, the solar corona can be seen with the naked eye, during the brief period of totality.

The parts of the Sun above the photosphere are referred to collectively as the *solar atmosphere*.[47] They can be viewed with telescopes operating across the electromagnetic spectrum, from radio through visible light to gamma rays, and comprise five principal zones: the *temperature minimum*, the chromosphere, the transition region, the corona, and the heliosphere.[47] The heliosphere, which may be considered the tenuous outer atmosphere of the Sun, extends outward past the orbit of Pluto to the heliopause, where it forms a sharp shock front boundary with the interstellar medium. The chromosphere, transition region, and corona are much hotter than the surface of the Sun.[47] The reason has not been conclusively proven; evidence suggests that Alfvén waves may have enough energy to heat the corona.[51]

The coolest layer of the Sun is a temperature minimum region about 500 km above the photosphere, with a temperature of about 4100 K.[47] This part of the Sun is cool enough to support simple molecules such as carbon monoxide and water, which can be detected by their absorption spectra.[52]

Above the temperature minimum layer is a layer about 2000 km thick, dominated by a spectrum of emission and absorption lines.[47] It is called the *chromosphere* from the Greek root *chroma*, meaning color, because the chromosphere is visible as a colored flash at the beginning and end of total eclipses of the Sun.[44] The temperature in the chromosphere increases gradually with altitude, ranging up to around 20000 K near the top.[47] In the upper part of chromosphere helium becomes partially ionized.[53]



Taken by Hinode's Solar Optical Telescope on January 12, 2007, this image of the Sun reveals the filamentary nature of the plasma connecting regions of different magnetic polarity.

Above the chromosphere, in a thin (about 200 km) transition region, the temperature rises rapidly from around 20,000 K in the upper chromosphere to coronal temperatures closer to 1,000,000 K.[54] The temperature increase is facilitated by the full ionization of helium in the transition region, which significantly reduces radiative cooling of the plasma.[53] The transition region does not occur at a well-defined altitude. Rather, it forms a kind of nimbus around chromospheric features such as spicules and filaments, and is in constant, chaotic motion.[44] The transition region is not easily visible from Earth's surface, but is readily observable from space by instruments sensitive to the extreme ultraviolet portion of the spectrum.[55]

The corona is the extended outer atmosphere of the Sun, which is much larger in volume than the Sun itself. The corona continuously expands into space forming the solar wind, which fills all the Solar System.[56] The low corona, which is very near the surface of the Sun, has a particle density around 10^{15}–10^{16} m^{-3}.[53] [57] The average temperature of the corona and solar wind is about 1,000,000–2,000,000 K; however, in the hottest regions it is 8,000,000–20,000,000 K.[54] While no complete theory yet exists to account for the temperature of the corona, at least some of its heat is known to be from magnetic reconnection.[54] [56]

The heliosphere, which is the cavity around the Sun filled with the solar wind plasma, extends from approximately 20 solar radii (0.1 AU) to the outer fringes of the Solar System. Its inner boundary is defined as the layer in which the flow of the solar wind becomes *superalfvénic*—that is, where the flow becomes faster than the speed of Alfvén waves.[58] Turbulence and dynamic forces outside this boundary cannot affect the shape of the solar corona within, because the information can only travel at the speed of Alfvén waves. The solar wind travels outward continuously through the heliosphere, forming the solar magnetic field into a spiral shape,[56] until it impacts the heliopause more than 50 AU from the Sun. In December 2004, the Voyager 1 probe passed through a shock front that is thought to be part of the heliopause. Both of the Voyager probes have recorded higher levels of energetic particles as they approach the boundary.[59]

Magnetic field

The heliospheric current sheet extends to the outer reaches of the Solar System, and results from the influence of the Sun's rotating magnetic field on the plasma in the interplanetary medium.[60]

The Sun is a magnetically active star. It supports a strong, changing magnetic field that varies year-to-year and reverses direction about every eleven years around solar maximum.[32] The Sun's magnetic field leads to many effects that are collectively called solar activity, including sunspots on the surface of the Sun, solar flares, and variations in solar wind that carry material through the Solar System.[32] Effects of solar activity on Earth include auroras at moderate to high latitudes, and the disruption of radio communications and electric power. Solar activity is thought to have played a large role in the formation and evolution of the Solar System. Solar activity changes the structure of Earth's outer atmosphere.[27]

All matter in the Sun is in the form of gas and plasma because of its high temperatures. This makes it possible for the Sun to rotate faster at its equator (about 25 days) than it does at higher latitudes (about 35 days near its poles). The differential rotation of the Sun's latitudes causes its magnetic field lines to become twisted together over time, causing magnetic field loops to erupt from the Sun's surface and trigger the formation of the Sun's dramatic sunspots and solar prominences (see magnetic reconnection). This twisting action creates the solar dynamo and an 11-year solar cycle of magnetic activity as the Sun's magnetic field reverses itself about every 11 years.[61] [62]

The solar magnetic field extends well beyond the Sun itself. The magnetized solar wind plasma carries Sun's magnetic field into the space forming what is called the interplanetary magnetic field.[56] Since the plasma can only move along the magnetic field lines, the interplanetary magnetic field is initially stretched radially away from the Sun. Because the fields above and below the solar equator have different polarities pointing towards and away from the Sun, there exists a thin current layer in the solar equatorial plane, which is called the heliospheric current sheet.[56] At the large distances the rotation of the Sun twists the magnetic field and the current sheet into the Archimedean spiral like structure called the Parker spiral.[56] The interplanetary magnetic field is much stronger than the dipole component of the solar magnetic field. The Sun's 50–400 μT (in the photosphere) magnetic dipole field reduces with the cube of the distance to about 0.1 nT at the distance of the Earth. However, according to spacecraft observations the interplanetary field at the Earth's location is about 100 times greater at around 5 nT.[63]

Chemical composition

The Sun is composed primarily of the chemical elements hydrogen and helium; they account for 74.9% and 23.8% of the mass of the Sun in the photosphere, respectively.[64] All heavier elements, called *metals* in astronomy, account for less than 2% of the mass. The most abundant metals are oxygen (roughly 1% of the Sun's mass), carbon (0.3%), neon (0.2%), and iron (0.2%).[65]

The Sun inherited its chemical composition from the interstellar medium out of which it formed: the hydrogen and helium in the Sun were produced by Big Bang nucleosynthesis. The metals were produced by stellar nucleosynthesis in generations of stars which completed their stellar evolution and returned their material to the interstellar medium before the formation of the Sun.[66] The chemical composition of the photosphere is normally considered representative of the composition of the primordial Solar System.[67] However, since the Sun formed, the helium and heavy elements have settled out of the photosphere. Therefore, the photosphere now contains slightly less helium and only 84% of the heavy elements than the protostellar Sun did; the protostellar Sun was 71.1% hydrogen, 27.4% helium, and 1.5% metals.[64]

In the inner portions of the Sun, nuclear fusion has modified the composition by converting hydrogen into helium, so the innermost portion of the Sun is now roughly 60% helium, with the metal abundance unchanged. Because the interior of the Sun is radiative, not convective (see Structure above), none of the fusion products from the core have risen to the photosphere.[68]

The solar heavy-element abundances described above are typically measured both using spectroscopy of the Sun's photosphere and by measuring abundances in meteorites that have never been heated to melting temperatures. These meteorites are thought to retain the composition of the protostellar Sun and thus not affected by settling of heavy elements. The two methods generally agree well.[13]

Singly ionized iron group elements

In the 1970s, much research focused on the abundances of iron group elements in the Sun.[69] [70] Although significant research was done, the abundance determination of some iron group elements (e.g., cobalt and manganese) was still difficult at least as far as 1978 because of their hyperfine structures.[69]

The first largely complete set of oscillator strengths of singly ionized iron group elements were made available first in the 1960s,[71] and improved oscillator strengths were computed in 1976.[72] In 1978 the abundances of singly ionized elements of the iron group were derived.[69]

Solar and planetary mass fractionation relationship

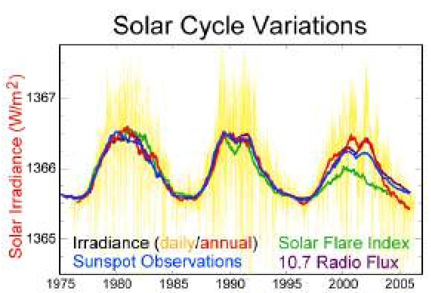
Various authors have considered the existence of a mass fractionation relationship between the isotopic compositions of solar and planetary noble gases,[73] for example correlations between isotopic compositions of planetary and solar neon and xenon.[74] Nevertheless, the belief that the whole Sun has the same composition as the solar atmosphere was still widespread, at least until 1983.[75]

In 1983, it was claimed that it was the fractionation in the Sun itself that caused the fractionation relationship between the isotopic compositions of planetary and solar wind implanted noble gases.[75]

Solar cycles

Sunspots and the sunspot cycle

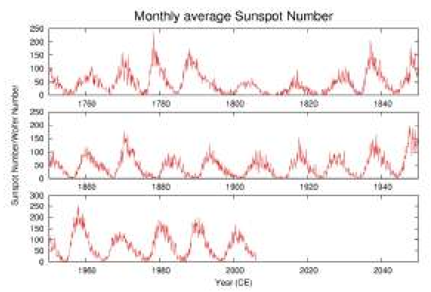
When observing the Sun with appropriate filtration, the most immediately visible features are usually its sunspots, which are well-defined surface areas that appear darker than their surroundings because of lower temperatures. Sunspots are regions of intense magnetic activity where convection is inhibited by strong magnetic fields, reducing energy transport from the hot interior to the surface. The magnetic field causes strong heating in the corona, forming active regions that are the source of intense solar flares and coronal mass ejections. The largest sunspots can be tens of thousands of kilometers across.[76]



Measurements of solar cycle variation during the last 30 years

The number of sunspots visible on the Sun is not constant, but varies over an 11-year cycle known as the solar cycle. At a typical solar minimum, few sunspots are visible, and occasionally none at all can be seen. Those that do appear are at high solar latitudes. As the sunspot cycle progresses, the number of sunspots increases and they move closer to the equator of the Sun, a phenomenon described by Spörer's law. Sunspots usually exist as pairs with opposite magnetic polarity. The magnetic polarity of the leading sunspot alternates every solar cycle, so that it will be a north magnetic pole in one solar cycle and a south magnetic pole in the next.[77]

The solar cycle has a great influence on space weather, and is a significant influence on the Earth's climate since luminosity has a direct relationship with magnetic activity.[78] Solar activity minima tend to be correlated with colder temperatures, and longer than average solar cycles tend to be correlated with hotter temperatures. In the 17th century, the solar cycle appears to have stopped entirely for several decades; very few sunspots were observed during this period. During this era, which is known as the Maunder minimum or Little Ice Age, Europe experienced very cold temperatures.[79] Earlier extended minima have been discovered through analysis of tree rings and appear to have coincided with lower-than-average global temperatures.[80]



History of the number of observed sunspots during the last 250 years, which shows the ~11-year solar cycle

Possible long-term cycle

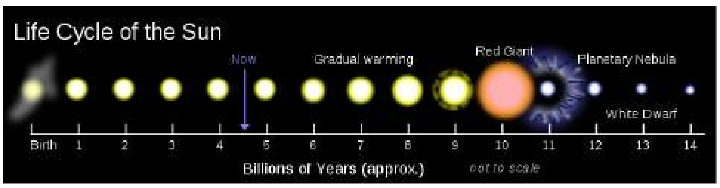
A recent theory claims that there are magnetic instabilities in the core of the Sun that cause fluctuations with periods of either 41,000 or 100,000 years. These could provide a better explanation of the ice ages than the Milankovitch cycles.[81] [82]

Life cycle

The Sun was formed about 4.57 billion years ago when a hydrogen molecular cloud collapsed.[32] Solar formation is dated in two ways: the Sun's current main sequence age, determined using computer models of stellar evolution and nucleocosmochronology, is thought to be about 4.57 billion years.[83] This is in close accord with the radiometric date of the oldest Solar System material, at 4.567 billion years ago.[84] [85]

The Sun is about halfway through its main-sequence evolution, during which nuclear fusion reactions in its core fuse hydrogen into helium. Each second, more than four million metric tons of matter are converted into energy within the Sun's core, producing neutrinos and solar radiation. At this rate, the Sun has so far converted around 100 Earth-masses of matter into energy. The Sun will spend a total of approximately 10 billion years as a main sequence star.[86]

The Sun does not have enough mass to explode as a supernova. Instead, in about 5 billion years, it will enter a red giant phase, its outer layers expanding as the hydrogen fuel in the core is consumed and the core contracts and heats up. Helium fusion will begin when the core temperature reaches around 100 million K and will produce carbon, entering the asymptotic giant branch phase.[30]



Life-cycle of the Sun; sizes are not drawn to scale.

Earth's fate is precarious. As a red giant, the Sun will have a maximum radius beyond the Earth's current orbit, 1 AU (1.5×10^{11} m), 250 times the present radius of the Sun.[87] However, by the time it is an asymptotic giant branch star, the Sun will have lost roughly 30% of its present mass due to a stellar wind, so the orbits of the planets will move outward. If it were only for this, Earth would probably be spared, but new research suggests that Earth will be swallowed by the Sun owing to tidal interactions.[87] Even if Earth would escape incineration in the Sun, still all its water will be boiled away and most of its atmosphere would escape into space. Even during its current life in the main sequence, the Sun is gradually becoming more luminous (about 10% every 1 billion years), and its surface temperature is slowly rising. The Sun used to be fainter in the past, which is possibly the reason life on Earth has only existed for about 1 billion years on land. The increase in solar temperatures is such that in about another billion years the surface of the Earth will likely become too hot for liquid water to exist, ending all terrestrial life.[87] [88]

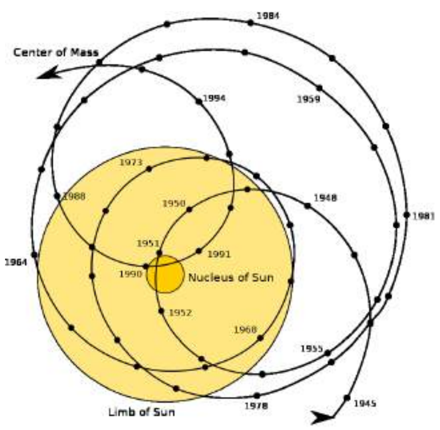
Following the red giant phase, intense thermal pulsations will cause the Sun to throw off its outer layers, forming a planetary nebula. The only object that will remain after the outer layers are ejected is the extremely hot stellar core, which will slowly cool and fade as a white dwarf over many billions of years. This stellar evolution scenario is typical of low- to medium-mass stars.[89] [90]

Sunlight

Sunlight is Earth's primary source of energy. The solar constant is the amount of power that the Sun deposits per unit area that is directly exposed to sunlight. The solar constant is equal to approximately 1368 W/m^2 (watts per square meter) at a distance of one astronomical unit (AU) from the Sun (that is, on or near Earth).[91] Sunlight on the surface of Earth is attenuated by the Earth's atmosphere so that less power arrives at the surface—closer to 1000 W/m^2 in clear conditions when the Sun is near the zenith.[92]

Solar energy can be harnessed by a variety of natural and synthetic processes—photosynthesis by plants captures the energy of sunlight and converts it to chemical form (oxygen and reduced carbon compounds), while direct heating or electrical conversion by solar cells are used by solar power equipment to generate electricity or to do other useful work, sometimes employing concentrating solar power (that it is measured in suns). The energy stored in petroleum and other fossil fuels was originally converted from sunlight by photosynthesis in the distant past.[27]

Motion and location within the galaxy



Motion of barycenter of Solar System relative to the Sun.

The Sun lies close to the inner rim of the Milky Way Galaxy's Orion Arm, in the Local Fluff or the Gould Belt, at a hypothesized distance of 7.5–8.5 kpc (25,000–28,000 lightyears) from the Galactic Center,[93] [94] [95] [96] contained within the Local Bubble, a space of rarefied hot gas, possibly produced by the supernova remnant, Geminga.[97] The distance between the local arm and the next arm out, the Perseus Arm, is about 6,500 light-years.[98] The Sun, and thus the Solar System, is found in what scientists call the galactic habitable zone.

The Apex of the Sun's Way, or the solar apex, is the direction that the Sun travels through space in the Milky Way, relative to other nearby stars. The general direction of the Sun's galactic motion is towards the star Vega in the constellation of Lyra at an angle of roughly 60 sky degrees to the direction of the Galactic Center.

The Sun's orbit around the Galaxy is expected to be roughly elliptical with the addition of perturbations due to the galactic spiral arms and non-uniform mass distributions. In addition the Sun oscillates up and down relative to the galactic plane approximately 2.7 times per orbit. This is very similar to how a simple harmonic oscillator works with no drag force (damping) term. It has been argued that the Sun's passage through the higher density spiral arms often coincides with mass extinctions on Earth, perhaps due to increased impact events.[99] It takes the Solar System about 225–250 million years to complete one orbit of the galaxy (a *galactic year*),[100] so it is thought to have completed 20–25 orbits during the lifetime of the Sun. The orbital speed of the Solar System about the center of the Galaxy is approximately 251 km/s.[101] At this speed, it takes around 1,190 years for the Solar System to travel a distance of 1 light-year, or 7 days to travel 1 AU.[102]

The Sun's motion about the centre of mass of the Solar System is complicated by perturbations from the planets. Every few hundred years this motion switches between prograde and retrograde.[103]

Theoretical problems

Solar neutrino problem

For many years the number of solar electron neutrinos detected on Earth was $^1/_3$ to $^1/_2$ of the number predicted by the standard solar model. This anomalous result was termed the solar neutrino problem. Theories proposed to resolve the problem either tried to reduce the temperature of the Sun's interior to explain the lower neutrino flux, or posited that electron neutrinos could oscillate—that is, change into undetectable tau and muon neutrinos as they traveled between the Sun and the Earth.[104] Several neutrino observatories were built in the 1980s to measure the solar neutrino flux as accurately as possible, including the Sudbury Neutrino Observatory and Kamiokande.[105] Results from these observatories eventually led to the discovery that neutrinos have a very small rest mass and do indeed oscillate.[106] [43] Moreover, in 2001 the Sudbury Neutrino Observatory was able to detect all three types of neutrinos directly, and found that the Sun's *total* neutrino emission rate agreed with the Standard Solar Model, although depending on the neutrino energy as few as one-third of the neutrinos seen at Earth are of the electron type.[105] [107] This proportion agrees with that predicted by the Mikheyev-Smirnov-Wolfenstein effect (also known as the matter effect), which describes neutrino oscillation in matter, and it is now considered a solved problem.[105]

Coronal heating problem

The optical surface of the Sun (the photosphere) is known to have a temperature of approximately 6,000 K. Above it lies the solar corona, rising to a temperature of 1,000,000–2,000,000 K.[54] The high temperature of the corona shows that it is heated by something other than direct heat conduction from the photosphere.[56]

It is thought that the energy necessary to heat the corona is provided by turbulent motion in the convection zone below the photosphere, and two main mechanisms have been proposed to explain coronal heating.[54] The first is wave heating, in which sound, gravitational or magnetohydrodynamic waves are produced by turbulence in the convection zone.[54] These waves travel upward and dissipate in the corona, depositing their energy in the ambient gas in the form of heat.[108] The other is magnetic heating, in which magnetic energy is continuously built up by photospheric motion and released through magnetic reconnection in the form of large solar flares and myriad similar but smaller events—nanoflares.[109]

Currently, it is unclear whether waves are an efficient heating mechanism. All waves except Alfvén waves have been found to dissipate or refract before reaching the corona.[110] In addition, Alfvén waves do not easily dissipate in the corona. Current research focus has therefore shifted towards flare heating mechanisms.[54]

Faint young Sun problem

Theoretical models of the Sun's development suggest that 3.8 to 2.5 billion years ago, during the Archean period, the Sun was only about 75% as bright as it is today. Such a weak star would not have been able to sustain liquid water on the Earth's surface, and thus life should not have been able to develop. However, the geological record demonstrates that the Earth has remained at a fairly constant temperature throughout its history, and that the young Earth was somewhat warmer than it is today. The consensus among scientists is that the young Earth's atmosphere contained much larger quantities of greenhouse gases (such as carbon dioxide, methane and/or ammonia) than are present today, which trapped enough heat to compensate for the smaller amount of solar energy reaching the planet.[111]

Present anomalies

The Sun is currently behaving unexpectedly in a number of ways.[112] [113]

- It is in the midst of an unusual sunspot minimum, lasting far longer and with a higher percentage of spotless days than normal; since May 2008.
- It is measurably dimming; its output has dropped 0.02% at visible wavelengths and 6% at EUV wavelengths in comparison with the levels at the last solar minimum.[114]
- Over the last two decades, the solar wind's speed has dropped by 3%, its temperature by 13%, and its density by 20%.[115]
- Its magnetic field is at less than half strength compared to the minimum of 22 years ago. The entire heliosphere, which fills the Solar System, has shrunk as a result, resulting in an increase in the level of cosmic radiation striking the Earth and its atmosphere.

History of observation

Early understanding and etymology

The Trundholm Sun chariot pulled by a horse is a sculpture believed to be illustrating an important part of Nordic Bronze Age mythology. The sculpture is probably from around 1350 BC. It is displayed at the National Museum of Denmark.

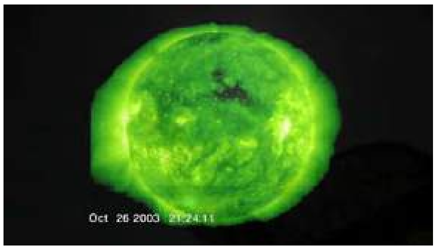
The English proper noun *sun* developed from Old English *sunne* (around 725, attested in *Beowulf*), and may be related to *south*. Cognates to English *sun* appear in other Germanic languages, including Old Frisian *sunne*, *sonne* ("sun"), Old Saxon *sunna*, Middle Dutch *sonne*, modern Dutch *zon*, Old High German *sunna*, modern German *Sonne*, Old Norse *sunna*, and Gothic *sunnō*. All Germanic terms for the Sun stem from Proto-Germanic **sunnōn*.[116] In Germanic paganism, the Sun is personified as a goddess; Sól/Sunna.[117]

Theories have been proposed that Sun, as Germanic goddess, may represent an extension of an earlier Proto-Indo-European deity due to Indo-European linguistic connections between Old Norse *Sól*, Sanskrit *Surya*, Gaulish *Sulis*, Lithuanian *Saulė*, and Slavic *Solnitse*.[117]

Humanity's most fundamental understanding of the Sun is as the luminous disk in the sky, whose presence above the horizon creates day and whose absence causes night. In many prehistoric and ancient cultures, the Sun was thought to be a solar deity or other supernatural phenomenon. Worship of the Sun was central to civilizations such as the Inca of South America and the Aztecs of what is now Mexico. Many ancient monuments were constructed with solar phenomena in mind; for example, stone megaliths accurately mark the summer or winter solstice (some of the most prominent megaliths are located in Nabta Playa, Egypt, Mnajdra, Malta and at Stonehenge, England); Newgrange, a prehistoric human-built mount in Ireland, was designed to detect the winter solstice; the pyramid of El Castillo at Chichén Itzá in Mexico is designed to cast shadows in the shape of serpents climbing the pyramid at the vernal and autumn equinoxes.

In the late Roman Empire the Sun's birthday was a holiday celebrated as Sol Invictus (literally "unconquered sun") soon after the winter solstice which may have been an antecedent to Christmas. Regarding the fixed stars, the Sun appears from Earth to revolve once a year along the ecliptic through the zodiac, and so Greek astronomers considered it to be one of the seven planets (Greek *planetes*, "wanderer"), after which the seven days of the week are named in some languages.[118] [119] [120]

Development of scientific understanding



Since the discovery of sunspots by Galileo in 1609, we have continued to study the Sun.

In the early first millennium BCE, Babylonian astronomers observed that the Sun's motion along the ecliptic was not uniform, though they were unaware of why this was; it is today known that this is due to the Earth moving in an elliptic orbit around the Sun, with the Earth moving faster when it is nearer to the Sun at perihelion and moving slower when it is farther away at aphelion.[121]

One of the first people to offer a scientific or philosophical explanation for the Sun was the Greek philosopher Anaxagoras, who reasoned that it was a giant flaming ball of metal even larger than the Peloponnesus rather than the chariot of Helios, and that the Moon reflected the light of the Sun.[122] For teaching this heresy, he was imprisoned by the authorities and sentenced to death, though he was later released through the intervention of Pericles. Eratosthenes estimated the distance between the Earth and the Sun in the 3rd century BCE as "of stadia myriads 400 and 80000", the translation of which is ambiguous, implying either 4,080,000 stadia (755,000 km) or 804,000,000 stadia (148 to 153 million kilometers or 0.99 to 1.02 AU); the latter value is correct to within a few percent. In the 1st century CE, Ptolemy estimated the distance as 1,210 times the Earth radius, approximately 7.71 million kilometers (0.0515 AU).[123]

The theory that the Sun is the center around which the planets move was first proposed by the ancient Greek Aristarchus of Samos in the 3rd century BCE, and later adopted by Seleucus of Seleucia (see Heliocentrism). This largely philosophical view was developed into fully predictive mathematical model of a heliocentric system in the 16th century by Nicolaus Copernicus. In the early 17th century, the invention of the telescope permitted detailed observations of sunspots by Thomas Harriot, Galileo Galilei and other astronomers. Galileo made some of the first known telescopic observations of sunspots and posited that they were on the surface of the Sun rather than small objects passing between the Earth and the Sun.[124] Sunspots were also observed since the Han Dynasty (206 BCE – 220 CE) by Chinese astronomers who maintained records of these observations for centuries. Averroes also provided a description of sunspots in the 12th century.[125]

Arabic astronomical contributions include Albatenius discovering that the direction of the Sun's eccentric is changing,[126] and Ibn Yunus observing more than 10,000 entries for the Sun's position for many years using a large astrolabe.[127] The transit of Venus was first observed in 1032 by Avicenna, who concluded that Venus is closer to the Earth than the Sun,[128] while one of the first observations of the transit of Mercury was conducted by Ibn Bajjah in the 12th century.[129]

In 1672 Giovanni Cassini and Jean Richer determined the distance to Mars and were thereby able to calculate the distance to the Sun. Isaac Newton observed the Sun's light using a prism, and showed that it was made up of light of many colors,[130] while in 1800 William Herschel discovered infrared radiation beyond the red part of the solar spectrum.[131] The 19th century saw spectroscopic studies of the Sun advance, and Joseph von Fraunhofer made the first observations of absorption lines in the spectrum, the strongest of which are still often referred to as Fraunhofer lines. When expanding the spectrum of light from the Sun, a large number of missing colors can be found.

In the early years of the modern scientific era, the source of the Sun's energy was a significant puzzle. Lord Kelvin suggested that the Sun was a gradually cooling liquid body that was radiating an internal store of heat.[132] Kelvin and Hermann von Helmholtz then proposed a gravitational contraction mechanism to explain the energy output. Unfortunately the resulting age estimate was only 20 million years, well short of the time span of at least 300 million years suggested by some geological discoveries of that time.[132] In 1890 Joseph Lockyer, who discovered helium in the solar spectrum, proposed a meteoritic hypothesis for the formation and evolution of the Sun.[133]

Not until 1904 was a documented solution offered. Ernest Rutherford suggested that the Sun's output could be maintained by an internal source of heat, and suggested radioactive decay as the source.[134] However, it would be

Albert Einstein who would provide the essential clue to the source of the Sun's energy output with his mass-energy equivalence relation $E = mc^2$.[135]

In 1920, Sir Arthur Eddington proposed that the pressures and temperatures at the core of the Sun could produce a nuclear fusion reaction that merged hydrogen (protons) into helium nuclei, resulting in a production of energy from the net change in mass.[136] The preponderance of hydrogen in the Sun was confirmed in 1925 by Cecilia Payne. The theoretical concept of fusion was developed in the 1930s by the astrophysicists Subrahmanyan Chandrasekhar and Hans Bethe. Hans Bethe calculated the details of the two main energy-producing nuclear reactions that power the Sun.[137] [138]

Finally, a seminal paper was published in 1957 by Margaret Burbidge, entitled "Synthesis of the Elements in Stars".[139] The paper demonstrated convincingly that most of the elements in the universe had been synthesized by nuclear reactions inside stars, some like our Sun.

Solar space missions

The first satellites designed to observe the Sun were NASA's Pioneers 5, 6, 7, 8 and 9, which were launched between 1959 and 1968. These probes orbited the Sun at a distance similar to that of the Earth, and made the first detailed measurements of the solar wind and the solar magnetic field. Pioneer 9 operated for a particularly long time, transmitting data until May 1983.[140] [141]

In the 1970s, two Helios spacecraft and the Skylab Apollo Telescope Mount provided scientists with significant new data on solar wind and the solar corona. The Helios 1 and 2 probes were U.S.–German collaborations that studied the solar wind from an orbit carrying the spacecraft inside Mercury's orbit at perihelion.[142] The Skylab space station, launched by NASA in 1973, included a solar observatory module called the Apollo Telescope Mount that was operated by astronauts resident on the station.[55] Skylab made the first time-resolved observations of the solar transition region and of ultraviolet emissions from the solar corona.[55] Discoveries included the first observations of coronal mass ejections, then called "coronal transients", and of coronal holes, now known to be intimately associated with the solar wind.[142]

In 1980, the Solar Maximum Mission was launched by NASA. This spacecraft was designed to observe gamma rays, X-rays and UV radiation from solar flares during a time of high solar activity and solar luminosity. Just a few months after launch, however, an electronics failure caused the probe to go into standby mode, and it spent the next three years in this inactive state. In 1984 Space Shuttle Challenger mission STS-41C retrieved the satellite and repaired its electronics before re-releasing it into orbit. The Solar Maximum Mission subsequently acquired thousands of images of the solar corona before re-entering the Earth's atmosphere in June 1989.[143]

Launched in 1991, Japan's Yohkoh (*Sunbeam*) satellite observed solar flares at X-ray wavelengths. Mission data allowed scientists to identify several different types of flares, and demonstrated that the corona away from regions of peak activity was much more dynamic and active than had previously been supposed. Yohkoh observed an entire solar cycle but went into standby mode when an annular eclipse in 2001 caused it to lose its lock on the Sun. It was destroyed by atmospheric re-entry in 2005.[144]

One of the most important solar missions to date has been the Solar and Heliospheric Observatory, jointly built by the European Space Agency and NASA and launched on 2 December 1995.[55] Originally intended to serve a two-year mission, a mission extension through 2012 was approved in October 2009.[145] It has proven so useful that a follow-on mission, the Solar Dynamics Observatory, was launched in February 2010.[146] Situated at the Lagrangian point between the Earth and the Sun (at which the gravitational pull from both is equal), SOHO has provided a constant view of the Sun at many wavelengths since its launch.[55] Besides its direct solar observation, SOHO has enabled the discovery of a large number of comets, mostly very tiny sungrazing comets which incinerate as they pass the Sun.[147]

All these satellites have observed the Sun from the plane of the ecliptic, and so have only observed its equatorial regions in detail. The Ulysses probe was launched in 1990 to study the Sun's polar regions. It first travelled to

Jupiter, to "slingshot" past the planet into an orbit which would take it far above the plane of the ecliptic. Serendipitously, it was well-placed to observe the collision of Comet Shoemaker-Levy 9 with Jupiter in 1994. Once Ulysses was in its scheduled orbit, it began observing the solar wind and magnetic field strength at high solar latitudes, finding that the solar wind from high latitudes was moving at about 750 km/s which was slower than expected, and that there were large magnetic waves emerging from high latitudes which scattered galactic cosmic rays.[148]

Elemental abundances in the photosphere are well known from spectroscopic studies, but the composition of the interior of the Sun is more poorly understood. A solar wind sample return mission, Genesis, was designed to allow astronomers to directly measure the composition of solar material. Genesis returned to Earth in 2004 but was damaged by a crash landing after its parachute failed to deploy on re-entry into Earth's atmosphere. Despite severe damage, some usable samples have been recovered from the spacecraft's sample return module and are undergoing analysis.[149]

The Solar Terrestrial Relations Observatory (STEREO) mission was launched in October 2006. Two identical spacecraft were launched into orbits that cause them to (respectively) pull further ahead of and fall gradually behind the Earth. This enables stereoscopic imaging of the Sun and solar phenomena, such as coronal mass ejections.[150] [151]

Observation and effects

The Sun as it appears from the surface of Earth

Sunlight is very bright, and looking directly at the Sun with the naked eye for brief periods can be painful, but is not particularly hazardous for normal, non-dilated eyes.[152] [153] Looking directly at the Sun causes phosphene visual artifacts and temporary partial blindness. It also delivers about 4 milliwatts of sunlight to the retina, slightly heating it and potentially causing damage in eyes that cannot respond properly to the brightness.[154] [155] UV exposure gradually yellows the lens of the eye over a period of years and is thought to contribute to the formation of cataracts, but this depends on general exposure to solar UV, not on whether one looks directly at the Sun.[156] Long-duration viewing of the direct Sun with the naked eye can begin to cause UV-induced, sunburn-like lesions on the retina after about 100 seconds, particularly under conditions where the UV light from the Sun is intense and well focused;[157] [158] conditions are worsened by young eyes or new lens implants (which admit more UV than aging natural eyes), Sun angles near the zenith, and observing locations at high altitude.

Viewing the Sun through light-concentrating optics such as binoculars is very hazardous without an appropriate filter that blocks UV and substantially dims the sunlight. An attenuating (ND) filter might not filter UV and so is still dangerous. Attenuating filters to view the Sun should be specifically designed for that use: some improvised filters pass UV or IR rays that can harm the eye at high brightness levels.[159] Unfiltered binoculars can deliver over 500 times as much energy to the retina as using the naked eye, killing retinal cells almost instantly (even though the power per unit area of image on the retina is the same, the heat cannot dissipate fast enough because the image is larger). Even brief glances at the midday Sun through unfiltered binoculars can cause permanent blindness.[160]

Partial solar eclipses are hazardous to view because the eye's pupil is not adapted to the unusually high visual contrast: the pupil dilates according to the total amount of light in the field of view, *not* by the brightest object in the field. During partial eclipses most sunlight is blocked by the Moon passing in front of the Sun, but the uncovered parts of the photosphere have the same surface brightness as during a normal day. In the overall gloom, the pupil expands from ~2 mm to ~6 mm, and each retinal cell exposed to the solar image receives about ten times more light than it would looking at the non-eclipsed Sun. This can damage or kill those cells, resulting in small permanent blind spots for the viewer.[161] The hazard is insidious for inexperienced observers and for children, because there is no perception of pain: it is not immediately obvious that one's vision is being destroyed.

During sunrise and sunset sunlight is attenuated due to Rayleigh scattering and Mie scattering from a particularly long passage through Earth's atmosphere,[162] and the Sun is sometimes faint enough to be viewed comfortably with the naked eye or safely with optics (provided there is no risk of bright sunlight suddenly appearing through a break between clouds). Hazy conditions, atmospheric dust, and high humidity contribute to this atmospheric attenuation.[163]

A rare optical phenomenon may occur shortly after sunset or before sunrise, known as a green flash. The flash is caused by light from the Sun just below the horizon being bent (usually through a temperature inversion) towards the observer. Light of shorter wavelengths (violet, blue, green) is bent more than that of longer wavelengths (yellow, orange, red) but the violet and blue light is scattered more, leaving light that is perceived as green.[164]

Ultraviolet light from the Sun has antiseptic properties and can be used to sanitize tools and water. It also causes sunburn, and has other medical effects such as the production of vitamin D. Ultraviolet light is strongly attenuated by Earth's ozone layer, so that the amount of UV varies greatly with latitude and has been partially responsible for many biological adaptations, including variations in human skin color in different regions of the globe.[165]

Terminology

Like other natural phenomena, the Sun has been an object of veneration in many cultures throughout human history, and was the source of the word Sunday. Its formal name in the English language is, per the International Astronomical Union, the Sun (capitalized as a proper noun).[166] The Latin name *Sol*, for the Sun god of the same name, pronounced /ˈsɒl/ (rhyming with *doll*) in English, is widely known but not common in general English language use; the adjectival form is the related word *solar*.[167] [168] "Sol" is, however, the modern word for "Sun" in many European languages.[169]

The term *sol* is also used by planetary astronomers to refer to the duration of a solar day on another planet, such as Mars.[170] A mean Earth solar day is approximately 24 hours, while a mean Martian 'sol' is 24 hours, 39 minutes, and 35.244 seconds.[171] See also Timekeeping on Mars.

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- Cohen, Richard (2010). *Chasing the Sun: the Epic Story of the Star that Gives us Life*. Simon & Schuster.

External links

- Nasa SOHO (Solar & Heliospheric Observatory) satellite (http://sohowww.nascom.nasa.gov/)
- National Solar Observatory (http://www.nso.edu)
- Astronomy Cast: The Sun (http://www.astronomycast.com/astronomy/episode-30-the-sun-spots-and-all/)
- Looking Into the Sun (http://www.life.com/image/first/in-gallery/47161/looking-into-the-sun) – slideshow by *Life magazine*
- A collection of spectacular images of the sun from various institutions (http://www.boston.com/bigpicture/2008/10/the_sun.html) (The Boston Globe)
- Satellite observations of solar luminosity (http://www.acrim.com)
- Sun|Trek, an educational website about the Sun (http://www.suntrek.org)
- The Swedish 1-meter Solar Telescope, SST (http://www.solarphysics.kva.se/)
- An animated explanation of the structure of the Sun (http://alienworlds.glam.ac.uk/sunStructure.html) (University of Glamorgan)
- The Future of our sun (http://www.youtube.com/watch?v=qpMRtvFD8ek&hl=fr)
- Solar Conveyor Belt Speeds Up (http://science.nasa.gov/headlines/y2010/12mar_conveyorbelt.htm) – NASA – images, link to report on Science

Planetary science

Planetary science is the scientific study of planets (including Earth), moons, and planetary systems, in particular those of the Solar System and the processes that form them. It studies objects ranging in size from micrometeoroids to gas giants, aiming to determine their composition, dynamics, formation, interrelations and history. It is a strongly interdisciplinary field, originally growing from astronomy and earth science,[1] but which now incorporates many disciplines, including planetary astronomy, planetary geology (together with geochemistry and geophysics), physical geography (geomorphology and cartography as applied to planets), atmospheric science, theoretical planetary science, and the study of extrasolar planets.[1] Allied disciplines include space physics, when concerned with the effects of the Sun on the bodies of the Solar System, and astrobiology.

There are interrelated observational and theoretical branches of planetary science. Observational research can involve a combination of space exploration, predominantly with robotic spacecraft missions using remote sensing, and comparative, experimental work in Earth-based laboratories. The theoretical component involves considerable computer simulation and mathematical modelling.

Photograph from Apollo 15 orbital unit of the rilles in the vicinity of the crater Aristarchus on the Moon. The arrangement of the two valleys is very similar, although one third the size, to Great Hungarian Plain rivers Danube and Tisza.

Planetary scientists are generally located in the astronomy and physics or earth sciences departments of universities or research centres, though there are several purely planetary science institutes worldwide. There are several major conferences each year, and a wide range of peer-reviewed journals.

History

The history of planetary science may be said to have begun with the Ancient Greek philosopher Democritus, who is reported by Hippolytus as saying

> "The ordered worlds are boundless and differ in size, and that in some there is neither sun nor moon, but that in others, both are greater than with us, and yet with others more in number. And that the intervals between the ordered worlds are unequal, here more and there less, and that some increase, others flourish and others decay, and here they come into being and there they are eclipsed. But that they are destroyed by colliding with one another. And that some ordered worlds are bare of animals and plants and all water."[2]

In more modern times, planetary science began in astronomy, from studies of the unresolved planets. In this sense, the original planetary astronomer would be Galileo, who discovered the four largest moons of Jupiter, the mountains on the Moon, and first observed the rings of Saturn, all objects of intense later study. Galileo's study of the lunar mountains in 1609 also began the study of extraterrestrial landscapes: his observation "that the Moon certainly does not possess a smooth and polished surface" suggested that it and other worlds might appear "just like the face of the Earth itself".[3]

Advances in telescope construction and instrumental resolution gradually allowed increased identification of the atmospheric and surface details of the planets. The Moon was initially the most heavily studied, as it always exhibited details on its surface, due to its proximity to the Earth, and the technological improvements gradually produced more detailed lunar geological knowledge. In this scientific process, the main instruments were astronomical optical telescopes (and later radio telescopes) and finally robotic exploratory spacecraft.

The Solar System has now been relatively well-studied, and a good overall understanding of the formation and evolution of this planetary system exists. However, there are large numbers of unsolved questions,[4] and the rate of new discoveries is very high, partly due to the large number of interplanetary spacecraft currently exploring the Solar System.

Disciplines

Planetary astronomy

This is both an observational and a theoretical science. Observational researchers are predominantly concerned with the study of the small bodies of the solar system: those that are observed by telescopes, both optical and radio, so that characteristics of these bodies such as shape, spin, surface materials and weathering are determined, and the history of their formation and evolution can be understood.

Theoretical planetary astronomy is concerned with dynamics: the application of the principles of celestial mechanics to the Solar System and extrasolar planetary systems.

Planetary geology

The best known research topics of planetary geology deal with the planetary bodies in the near vicinity of the Earth: the Moon, and the two neighbouring planets: Venus and Mars. Of these, the Moon was studied first, using methods developed earlier on the Earth.

Geomorphology

Geomorphology studies the features on planetary surfaces and reconstructs the history of their formation, inferring the physical processes that acted on the surface. Planetary geomorphology includes study of several classes of surface feature:

- Impact features (multi-ringed basins, craters)
- Volcanic and tectonic features (lava flows, fissures, rilles)
- Space weathering - erosional effects generated by the harsh environment of space (continuous micrometeorite bombardment, high-energy particle rain, impact gardening). For example, the thin dust cover on the surface of the lunar regolith is a result of micrometeorite bombardment.
- Hydrological features: the liquid involved can range from water to hydrocarbon and ammonia, depending on the location within the Solar System.

The history of a planetary surface can be deciphered by mapping features from top to bottom according to their deposition sequence, as first determined on terrestrial strata by Nicolas Steno. For example, stratigraphic mapping prepared the Apollo astronauts for the field geology they would encounter on their lunar missions. Overlapping sequences were identified on images taken by the Lunar Orbiter program, and these were used to prepare a lunar stratigraphic column and geological map of the Moon.

Cosmochemistry, geochemistry and petrology

One of the main problems when generating hypotheses on the formation and evolution of objects in the Solar System is the lack of samples that can be analysed in the laboratory, where a large suite of tools are available and the full body of knowledge derived from terrestrial geology can be brought to bear. Fortunately, direct samples from the Moon, asteroids and Mars are present on Earth, removed from their parent bodies and delivered as meteorites. Some of these have suffered contamination from the oxidising effect of Earth's atmosphere and the infiltration of the biosphere, but those meteorites collected in the last few decades from Antarctica are almost entirely pristine.

The different types of meteorite that originate from the asteroid belt cover almost all parts of the structure of differentiated bodies: meteorites even exist that come from the core-mantle boundary (pallasites). The combination of geochemistry and observational astronomy has also made it possible to trace the HED meteorites back to a specific asteroid in the main belt, 4 Vesta.

The comparatively few known Martian meteorites have provided insight into the geochemical composition of the Martian crust, although the unavoidable lack of information about their points of origin on the diverse Martian surface has meant that they do not provide more detailed constraints on theories of the evolution of the Martian lithosphere. About 50 Martian meteorites have been identified, as of 2008.

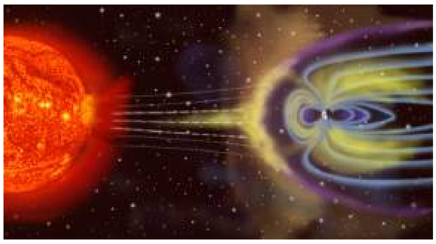
During the Apollo era, in the Apollo program, 384 kilograms of lunar samples were collected and transported to the Earth, and 3 Soviet Luna robots also delivered regolith samples from the Moon. These samples provide the most comprehensive record of the composition of any Solar System body beside the Earth. About 100 paired lunar meteorites are also known, as of 2008.

Geophysics

Space probes made it possible to collect data not only the visible light region, but in other areas of the electromagnetic spectrum. The planets can be characterized by their force fields: gravity and their magnetic fields, which are studied through geophysics and space physics.

Measuring the changes in acceleration experienced by spacecraft as they orbit has allowed fine details of the gravity fields of the planets to be mapped. For example, in the 1970s, the gravity field disturbances above lunar maria were measured through lunar orbiters, which lead to the discovery of concentrations of mass, mascons, beneath the Imbrium, Serenitatis, Crisium, Nectaris and Humorum basins.

If a planet's magnetic field is sufficiently strong, its interaction with the solar wind forms a magnetosphere around a planet. Early space probes discovered the gross dimensions of the terrestrial magnetic field, which extends about 10 Earth radiii towards the Sun. The solar wind, a stream of charged particles, streams out and around the terrestrial magnetic field, and continues behind the magnetic tail, hundreds of Earth radii downstream. Inside the magnetosphere, there are relatively dense regions of solar wind particles, the Van Allen radiation belts.



The solar wind is deflected by the magnetosphere (not to scale)

Atmospheric science

The atmosphere is an important transitional zone between the solid planetary surface and the higher rarefied ionizing and radiation belts. Not all planets have atmospheres: their existence depends on the mass of the planet, and the planet's distance from the Sun — too distant and frozen atmospheres occur. Besides the four gas giant planets, almost all of the terrestrial planets (Earth, Venus, and Mars) have significant atmospheres. Two moons have significant atmospheres: Saturn's moon Titan and Neptune's moon Triton. A tenuous atmosphere exists around Mercury.


Cloud bands clearly visible on Jupiter.

The effects of the rotation rate of a planet about its axis can be seen in atmospheric streams and currents. Seen from space, these features show as bands and eddies in the cloud system, and are particularly visible on Jupiter and Saturn.

Comparative planetary science

Planetary science frequently makes use of the method of comparison to give greater understanding of the object of study. This can involve comparing the dense atmospheres of Earth and Saturn's moon Titan, the evolution of outer Solar System objects at different distances from the Sun, or the geomorphology of the surfaces of the terrestrial planets, to give only a few examples.

The main comparison that can be made is to features on the Earth, as it is much more accessible and allows a much greater range of measurements to be made. Earth analogue studies are particularly common in planetary geology, geomorphology, and also in atmospheric science.

Professional activity

Journals

- *Icarus*
- *Journal of Geophysical Research—Planets*
- *Earth and Planetary Science Letters*
- *Geochimica et Cosmochimica Acta*
- *Meteoritics and Planetary Science*
- *Planetary and Space Science*

Professional bodies

- Division for Planetary Sciences (DPS) of the American Astronomical Society
- Meteoritical Society
- Europlanet

Major conferences

- Lunar and Planetary Science Conference (LPSC), organized by the Lunar and Planetary Institute in Houston. Held annually since 1970, occurs in March.
- American Geophysical Union (AGU) Joint Assembly (co-sponsored with other societies) in April-May, in various locations around the world.

- Meteoritical Society annual meeting, held during the Northern Hemisphere summer, generally alternating between North America and Europe.
- European Planetary Science Congress (EPSC), held annually around September at a location within Europe.
- DPS annual meeting, held around October at a different location each year, predominantly within the mainland US.
- AGU annual meeting in December in San Francisco.

Smaller workshops and conferences on particular fields occur worldwide throughout the year.

Major institutions

This non-exhaustive list includes those institutions and universities with major groups of people working in planetary science.

- European Space Agency
- NASA: Considerable number of research groups, including the JPL, GSFC, Ames
- MIT Dept. of Earth, Atmospheric and Planetary Sciences [5]
- Lunar and Planetary Institute
- University of Arizona's Lunar and Planetary Lab [6]
- University of California Santa Cruz's Department of Earth & Planetary Sciences [7]
- UCLA Dept. of Earth and Space Sciences [8]
- Caltech's Division of Geological and Planetary Sciences [9]
- Brown University Planetary Geosciences Group [10]
- University of Hawaii's Hawaii Institute of Geophysics and Planetology [11]
- University of Copenhagen's Center for Planetary Research
- University of Central Florida Planetary Sciences Group [12]
- University of British Columbia Institute for Planetary Science [13]
- University of Western Ontario - CPSX
- Open University Planetary and Space Sciences Research Institute [14]
- Planetary Science Institute
- The Australian National University's Planetary Science Institute [15]
- University of Tennessee Planetary Geoscience [16]

Basic concepts

- Asteroid
- Celestial mechanics
- Comet
- Extrasolar planet
- Gas giant
- Icy moon
- Kuiper belt
- Magnetosphere
- Planet
- Planetary differentiation
- Planetary system
- Definition of a planet
- Space weather
- Terrestrial planet

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[3] Taylor, Stuart Ross (1994). "Silent upon a peak in Darien". *Nature* **369** (6477): 196–7. Bibcode 1994Natur.369..196T. doi:10.1038/369196a0.
[4] Stern, Alan. "Ten Things I Wish We Really Knew In Planetary Science" (http://www.planetary.org/blog/article/00001956/). . Retrieved 2009-05-22.
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[10] http://www.planetary.brown.edu/
[11] http://www.higp.hawaii.edu/
[12] http://planets.ucf.edu/
[13] http://www.ibsubc.org/
[14] http://pssri.open.ac.uk/
[15] http://rsaa.anu.edu.au/PSI/Welcome.html
[16] http://web.eps.utk.edu/research/Planetary.html

Further reading

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- Morrison, David. 1994. *Exploring Planetary Worlds*. W.H. Freeman.

External links

- Planetary Science Research Discoveries (http://www.psrd.hawaii.edu/) (articles)
- The Planetary Society (http://www.planetary.org/home/) (world's largest space-interest group: see also their active news blog (http://www.planetary.org/blog/))
- Planetary Exploration Newsletter (http://planetarynews.org/) (PSI-published professional newsletter, weekly distribution)
- Women in Planetary Science (http://womeninplanetaryscience.wordpress.com/) (professional networking and news)

Planetary geology

Planetary geology, alternatively known as **astrogeology** or **exogeology**, is a planetary science discipline concerned with the geology of the celestial bodies such as the planets and their moons, asteroids, comets, and meteorites. Although the geo- prefix typically indicates topics of or relating to the Earth, planetary geology is named as such for historical and convenience reasons. Due to the types of investigations involved, it is also closely linked with Earth-based geology.

Planetary geologist and NASA astronaut Harrison "Jack" Schmitt collecting lunar samples during the Apollo 17 mission

Planetary geology includes such topics as determining the internal structure of the terrestrial planets, and also looks at planetary volcanism and surface processes such as impact craters, fluvial and aeolian processes. The structures of the giant planets and their moons are also examined, as is the make-up of the minor bodies of the solar system, such as asteroids, the Kuiper Belt, and comets.

Eugene Shoemaker is credited with creating the Branch of Astrogeology (now called the Astrogeology Research Program) within the U.S. Geological Survey. He made important contributions to the field and the study of impact craters, Lunar Science, asteroids, and comets.

The Visitor Center at Barringer Meteor Crater near Winslow, Arizona includes a Museum of Astrogeology.

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Star

A **star** is a massive, luminous ball of plasma held together by gravity. At the end of its lifetime, a star can also contain a proportion of degenerate matter. The nearest star to Earth is the Sun, which is the source of most of the energy on Earth. Other stars are visible from Earth during the night when they are not outshone by the Sun or blocked by atmospheric phenomena. Historically, the most prominent stars on the celestial sphere were grouped together into constellations and asterisms, and the brightest stars gained proper names. Extensive catalogues of stars have been assembled by astronomers, which provide standardized star designations.

A star-forming region in the Large Magellanic Cloud. NASA/ESA image

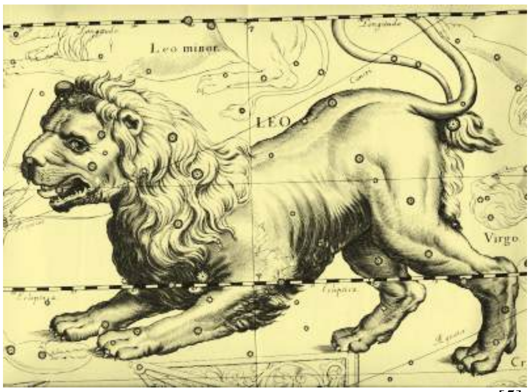
For at least a portion of its life, a star shines due to thermonuclear fusion of hydrogen in its core releasing energy that traverses the star's interior and then radiates into outer space. Almost all naturally occurring elements heavier than helium were created by stars, either via stellar nucleosynthesis during their lifetimes or by supernova nucleosynthesis when stars explode. Astronomers can determine the mass, age, chemical composition and many other properties of a star by observing its spectrum, luminosity and motion through space. The total mass of a star is the principal determinant in its evolution and eventual fate. Other characteristics of a star are determined by its evolutionary history, including diameter, rotation, movement and temperature. A plot of the temperature of many stars against their luminosities, known as a Hertzsprung-Russell diagram (H–R diagram), allows the age and evolutionary state of a star to be determined.

A star begins as a collapsing cloud of material composed primarily of hydrogen, along with helium and trace amounts of heavier elements. Once the stellar core is sufficiently dense, some of the hydrogen is steadily converted into helium through the process of nuclear fusion.[1] The remainder of the star's interior carries energy away from the core through a combination of radiative and convective processes. The star's internal pressure prevents it from collapsing further under its own gravity. Once the hydrogen fuel at the core is exhausted, those stars having at least 0.4 times the mass of the Sun[2] expand to become a red giant, in some cases fusing heavier elements at the core or in shells around the core. The star then evolves into a degenerate form, recycling a portion of the matter into the interstellar environment, where it will form a new generation of stars with a higher proportion of heavy elements.[3]

Binary and multi-star systems consist of two or more stars that are gravitationally bound, and generally move around each other in stable orbits. When two such stars have a relatively close orbit, their gravitational interaction can have a significant impact on their evolution.[4] Stars can form part of a much larger gravitationally bound structure, such as a cluster or a galaxy.

Observation history

Historically, stars have been important to civilizations throughout the world. They have been part of religious practices and used for celestial navigation and orientation. Many ancient astronomers believed that stars were permanently affixed to a heavenly sphere, and that they were immutable. By convention, astronomers grouped stars into constellations and used them to track the motions of the planets and the inferred position of the Sun.[5] The motion of the Sun against the background stars (and the horizon) was used to create calendars, which could be used to regulate agricultural practices.[7] The Gregorian calendar, currently used nearly everywhere in the world, is a solar calendar based on the angle of the Earth's rotational axis relative to its local star, the Sun.



People have seen patterns in the stars since ancient times.[5] This 1690 depiction of the constellation of Leo, the lion, is by Johannes Hevelius.[6]

The oldest accurately dated star chart appeared in ancient Egyptian astronomy in 1534 BC.[8] The earliest known star catalogues were compiled by the ancient Babylonian astronomers of Mesopotamia in the late 2nd millennium BC, during the Kassite Period (*ca.* 1531-1155 BC).[9]

The first star catalogue in Greek astronomy was created by Aristillus in approximately 300 BC, with the help of Timocharis.[10] The star catalog of Hipparchus (2nd century BC) included 1020 stars and was used to assemble Ptolemy's star catalogue.[11] Hipparchus is known for the discovery of the first recorded *nova* (new star).[12] Many of the constellations and star names in use today derive from Greek astronomy.

In spite of the apparent immutability of the heavens, Chinese astronomers were aware that new stars could appear.[13] In 185 AD, they were the first to observe and write about a supernova, now known as the SN 185.[14] The brightest stellar event in recorded history was the SN 1006 supernova, which was observed in 1006 and written about by the Egyptian astronomer Ali ibn Ridwan and several Chinese astronomers.[15] The SN 1054 supernova, which gave birth to the Crab Nebula, was also observed by Chinese and Islamic astronomers.[16] [17] [18]

Medieval Islamic astronomers gave Arabic names to many stars that are still used today, and they invented numerous astronomical instruments that could compute the positions of the stars. They built the first large observatory research institutes, mainly for the purpose of producing *Zij* star catalogues.[19] Among these, the *Book of Fixed Stars* (964) was written by the Persian astronomer Abd al-Rahman al-Sufi, who discovered a number of stars, star clusters (including the Omicron Velorum and Brocchi's Clusters) and galaxies (including the Andromeda Galaxy).[20] In the 11th century, the Persian polymath scholar Abu Rayhan Biruni described the Milky Way galaxy as a multitude of fragments having the properties of nebulous stars, and also gave the latitudes of various stars during a lunar eclipse in 1019.[21]

The Andalusian astronomer Ibn Bajjah proposed that the Milky Way was made up of many stars which almost touched one another and appeared to be a continuous image due to the effect of refraction from sublunary material, citing his observation of the conjunction of Jupiter and Mars on 500 AH (1106/1107 AD) as evidence.[22]

Early European astronomers such as Tycho Brahe identified new stars in the night sky (later termed *novae*), suggesting that the heavens were not immutable. In 1584 Giordano Bruno suggested that the stars were actually other suns, and may have other planets, possibly even Earth-like, in orbit around them,[23] an idea that had been suggested earlier by the ancient Greek philosophers, Democritus and Epicurus,[24] and by medieval Islamic cosmologists[25] such as Fakhr al-Din al-Razi.[26] By the following century, the idea of the stars as distant suns was reaching a consensus among astronomers. To explain why these stars exerted no net gravitational pull on the solar system, Isaac Newton suggested that the stars were equally distributed in every direction, an idea prompted by the theologian Richard Bentley.[27]

The Italian astronomer Geminiano Montanari recorded observing variations in luminosity of the star Algol in 1667. Edmond Halley published the first measurements of the proper motion of a pair of nearby "fixed" stars, demonstrating that they had changed positions from the time of the ancient Greek astronomers Ptolemy and Hipparchus. The first direct measurement of the distance to a star (61 Cygni at 11.4 light-years) was made in 1838 by Friedrich Bessel using the parallax technique. Parallax measurements demonstrated the vast separation of the stars in the heavens.[23]

William Herschel was the first astronomer to attempt to determine the distribution of stars in the sky. During the 1780s, he performed a series of gauges in 600 directions, and counted the stars observed along each line of sight. From this he deduced that the number of stars steadily increased toward one side of the sky, in the direction of the Milky Way core. His son John Herschel repeated this study in the southern hemisphere and found a corresponding increase in the same direction.[28] In addition to his other accomplishments, William Herschel is also noted for his discovery that some stars do not merely lie along the same line of sight, but are also physical companions that form binary star systems.

The science of stellar spectroscopy was pioneered by Joseph von Fraunhofer and Angelo Secchi. By comparing the spectra of stars such as Sirius to the Sun, they found differences in the strength and number of their absorption lines—the dark lines in a stellar spectra due to the absorption of specific frequencies by the atmosphere. In 1865 Secchi began classifying stars into spectral types.[29] However, the modern version of the stellar classification scheme was developed by Annie J. Cannon during the 1900s.

Observation of double stars gained increasing importance during the 19th century. In 1834, Friedrich Bessel observed changes in the proper motion of the star Sirius, and inferred a hidden companion. Edward Pickering discovered the first spectroscopic binary in 1899 when he observed the periodic splitting of the spectral lines of the star Mizar in a 104 day period. Detailed observations of many binary star systems were collected by astronomers such as William Struve and S. W. Burnham, allowing the masses of stars to be determined from computation of the orbital elements. The first solution to the problem of deriving an orbit of binary stars from telescope observations was made by Felix Savary in 1827.[30]

The twentieth century saw increasingly rapid advances in the scientific study of stars. The photograph became a valuable astronomical tool. Karl Schwarzschild discovered that the color of a star, and hence its temperature, could be determined by comparing the visual magnitude against the photographic magnitude. The development of the photoelectric photometer allowed very precise measurements of magnitude at multiple wavelength intervals. In 1921 Albert A. Michelson made the first measurements of a stellar diameter using an interferometer on the Hooker telescope.[31]

Important conceptual work on the physical basis of stars occurred during the first decades of the twentieth century. In 1913, the Hertzsprung-Russell diagram was developed, propelling the astrophysical study of stars. Successful models were developed to explain the interiors of stars and stellar evolution. The spectra of stars were also successfully explained through advances in quantum physics. This allowed the chemical composition of the stellar atmosphere to be determined.[32]

With the exception of supernovae, individual stars have primarily been observed in our Local Group of galaxies,[33] and especially in the visible part of the Milky Way (as demonstrated by the detailed star catalogues available for our galaxy[34]). But some stars have been observed in the M100 galaxy of the Virgo Cluster, about 100 million light years from the Earth.[35] In the Local Supercluster it is possible to see star clusters, and current telescopes could in principle observe faint individual stars in the Local Cluster—the most distant stars resolved have up to hundred million light years away[36] (see Cepheids). However, outside the Local Supercluster of galaxies, neither individual stars nor clusters of stars have been observed. The only exception is a faint image of a large star cluster containing hundreds of thousands of stars located one billion light years away[37] —ten times the distance of the most distant star cluster previously observed.

Designations

The concept of the constellation was known to exist during the Babylonian period. Ancient sky watchers imagined that prominent arrangements of stars formed patterns, and they associated these with particular aspects of nature or their myths. Twelve of these formations lay along the band of the ecliptic and these became the basis of astrology.[38] Many of the more prominent individual stars were also given names, particularly with Arabic or Latin designations.

As well as certain constellations and the Sun itself, stars as a whole have their own myths.[39] To the Ancient Greeks, some "stars", known as planets (Greek πλανήτης (planētēs), meaning "wanderer"), represented various important deities, from which the names of the planets Mercury, Venus, Mars, Jupiter and Saturn were taken.[39] (Uranus and Neptune were also Greek and Roman gods, but neither planet was known in Antiquity because of their low brightness. Their names were assigned by later astronomers.)

Circa 1600, the names of the constellations were used to name the stars in the corresponding regions of the sky. The German astronomer Johann Bayer created a series of star maps and applied Greek letters as designations to the stars in each constellation. Later a numbering system based on the star's right ascension was invented and added to John Flamsteed's star catalogue in his book *"Historia coelestis Britannica"* (the 1712 edition), whereby this numbering system came to be called *Flamsteed designation* or *Flamsteed numbering*.[40] [41]

Under space law, the only internationally recognized authority for naming celestial bodies is the International Astronomical Union (IAU).[42] A number of private companies sell names of stars, which the British Library calls an unregulated commercial enterprise.[43] [44] However, the IAU has disassociated itself from this commercial practice, and these names are neither recognized by the IAU nor used by them.[45] One such star naming company is the International Star Registry, which, during the 1980s, was accused of deceptive practice for making it appear that the assigned name was official. This ISR practice has been informally labeled a scam and a fraud,[46] [47] [48] [49] and the New York City Department of Consumer Affairs issued a violation against ISR for engaging in a deceptive trade practice.[50] [51]

Units of measurement

Most stellar parameters are expressed in SI units by convention, but CGS units are also used (e.g., expressing luminosity in ergs per second). Mass, luminosity, and radii are usually given in solar units, based on the characteristics of the Sun:

solar mass:	$M_{\odot} = 1.9891 \times 10^{30}$ kg[52]
solar luminosity:	$L_{\odot} = 3.827 \times 10^{26}$ watts[52]
solar radius:	$R_{\odot} = 6.960 \times 10^{8}$ m[53]

Large lengths, such as the radius of a giant star or the semi-major axis of a binary star system, are often expressed in terms of the astronomical unit (AU)—approximately the mean distance between the Earth and the Sun (150 million km or 93 million miles).

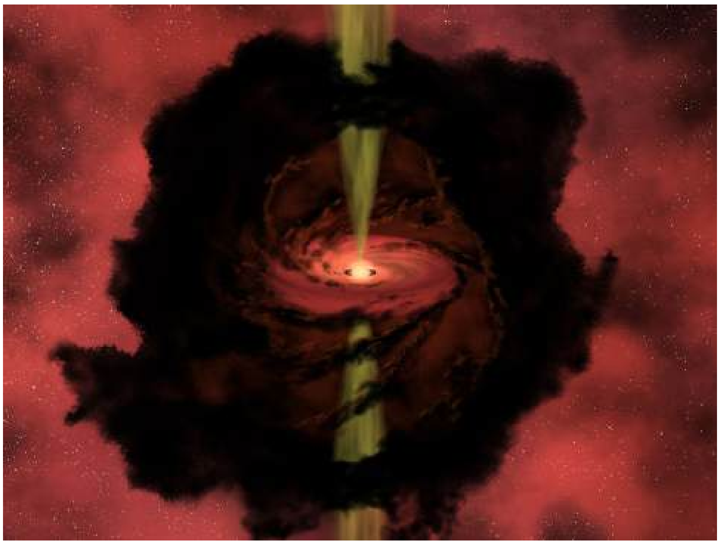
Formation and evolution

Stars are formed within extended regions of higher density in the interstellar medium, although the density is still lower than the inside of an earthly vacuum chamber. These regions are called *molecular clouds* and consist mostly of hydrogen, with about 23–28% helium and a few percent heavier elements. One example of such a star-forming region is the Orion Nebula.[54] As massive stars are formed from molecular clouds, they powerfully illuminate those clouds. They also ionize the hydrogen, creating an H II region.

Protostar formation

The formation of a star begins with a gravitational instability inside a molecular cloud, often triggered by shock waves from supernovae (massive stellar explosions) or the collision of two galaxies (as in a starburst galaxy). Once a region reaches a sufficient density of matter to satisfy the criteria for Jeans instability it begins to collapse under its own gravitational force.[55]

As the cloud collapses, individual conglomerations of dense dust and gas form what are known as Bok globules. As a globule collapses and the density increases, the gravitational energy is converted into heat and the temperature rises. When the protostellar cloud has approximately reached the stable condition of hydrostatic equilibrium, a protostar forms at the core.[56] These pre–main sequence stars are often surrounded by a protoplanetary disk. The period of gravitational contraction lasts for about 10–15 million years.



Artist's conception of the birth of a star within a dense molecular cloud. *NASA image*

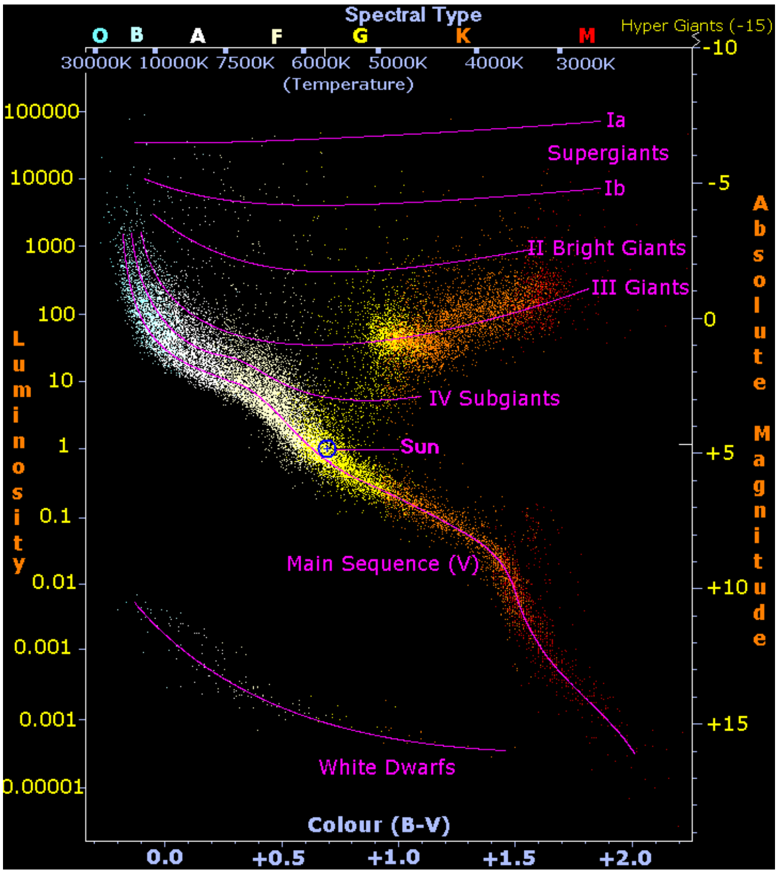
Early stars of less than 2 solar masses are called T Tauri stars, while those with greater mass are Herbig Ae/Be stars. These newly born stars emit jets of gas along their axis of rotation, which may reduce the angular momentum of the collapsing star and result in small patches of nebulosity known as Herbig-Haro objects.[57] [58] These jets, in combination with radiation from nearby massive stars, may help to drive away the surrounding cloud in which the star was formed.[59]

Main sequence

Stars spend about 90% of their lifetime fusing hydrogen to produce helium in high-temperature and high-pressure reactions near the core. Such stars are said to be on the main sequence and are called dwarf stars. Starting at zero-age main sequence, the proportion of helium in a star's core will steadily increase. As a consequence, in order to maintain the required rate of nuclear fusion at the core, the star will slowly increase in temperature and luminosity[60] –the Sun, for example, is estimated to have increased in luminosity by about 40% since it reached the main sequence 4.6 billion years ago.[61]

Every star generates a stellar wind of particles that causes a continual outflow of gas into space. For most stars, the amount of mass lost is negligible. The Sun loses 10^{-14} solar masses every year,[62] or about 0.01% of its total mass over its entire lifespan. However very massive stars can lose 10^{-7} to 10^{-5} solar masses each year, significantly affecting their evolution.[63] Stars that begin with more than 50 solar masses can lose over half their total mass while they remain on the main sequence.[64]

The duration that a star spends on the main sequence depends primarily on the amount of fuel it has to fuse and the rate at which it fuses that fuel, i.e. its initial mass and its luminosity. For the Sun, this is estimated to be about 10^{10} years. Large stars consume their fuel very rapidly and are short-lived. Small stars (called red dwarfs) consume their fuel very slowly and last tens to hundreds of billions of years. At the end of their lives, they simply become dimmer and dimmer.[2] However, since the lifespan of such stars is greater than the current age of the universe (13.7 billion years), no red dwarfs are expected to have yet reached this state.



An example of a Hertzsprung–Russell diagram for a set of stars that includes the Sun (center). (See "Classification" below.)

Besides mass, the portion of elements heavier than helium can play a significant role in the evolution of stars. In astronomy all elements heavier than helium are considered a "metal", and the chemical concentration of these elements is called the metallicity. The metallicity can influence the duration that a star will burn its fuel, control the formation of magnetic fields[65] and modify the strength of the stellar wind.[66] Older, population II stars have substantially less metallicity than the younger, population I stars due to the composition of the molecular clouds from which they formed. (Over time these clouds become increasingly enriched in heavier elements as older stars die and shed portions of their atmospheres.)

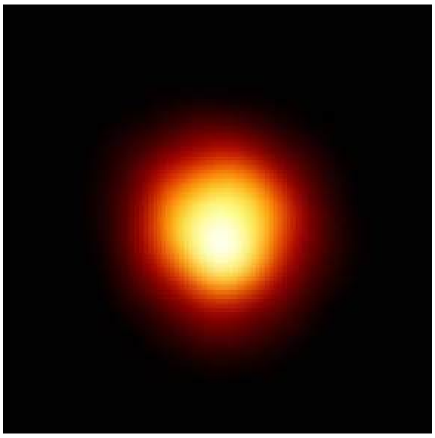
Post-main sequence

As stars of at least 0.4 solar masses[2] exhaust their supply of hydrogen at their core, their outer layers expand greatly and cool to form a red giant. For example, in about 5 billion years, when the Sun is a red giant, it will expand out to a maximum radius of roughly 1 astronomical unit (150 million kilometres), 250 times its present size. As a giant, the Sun will lose roughly 30% of its current mass.[61] [67]

In a red giant of up to 2.25 solar masses, hydrogen fusion proceeds in a shell-layer surrounding the core.[68] Eventually the core is compressed enough to start helium fusion, and the star now gradually shrinks in radius and increases its surface temperature. For larger stars, the core region transitions directly from fusing hydrogen to fusing helium.[69]

After the star has consumed the helium at the core, fusion continues in a shell around a hot core of carbon and oxygen. The star then follows an evolutionary path that parallels the original red giant phase, but at a higher surface temperature.

Massive stars


Betelgeuse is a red supergiant star approaching the end of its life cycle.

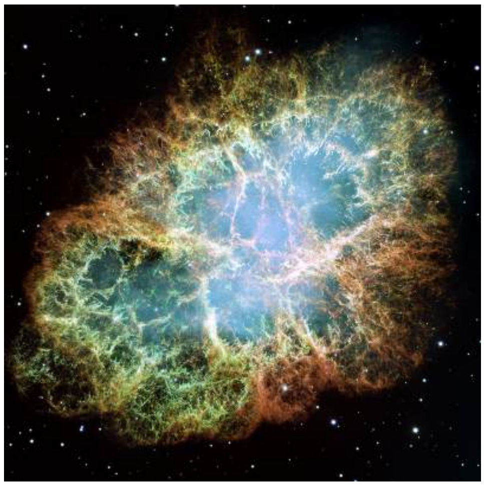
During their helium-burning phase, very high mass stars with more than nine solar masses expand to form red supergiants. Once this fuel is exhausted at the core, they can continue to fuse elements heavier than helium.

The core contracts until the temperature and pressure are sufficient to fuse carbon (see carbon burning process). This process continues, with the successive stages being fueled by neon (see neon burning process), oxygen (see oxygen burning process), and silicon (see silicon burning process). Near the end of the star's life, fusion can occur along a series of onion-layer shells within the star. Each shell fuses a different element, with the outermost shell fusing hydrogen; the next shell fusing helium, and so forth.[70]

The final stage is reached when the star begins producing iron. Since iron nuclei are more tightly bound than any heavier nuclei, if they are fused they do not release energy—the process would, on the contrary, consume energy. Likewise, since they are more tightly bound than all lighter nuclei, energy cannot be released by fission.[68] In relatively old, very massive stars, a large core of inert iron will accumulate in the center of the star. The heavier elements in these stars can work their way up to the surface, forming evolved objects known as Wolf-Rayet stars that have a dense stellar wind which sheds the outer atmosphere.

Collapse

An evolved, average-size star will now shed its outer layers as a planetary nebula. If what remains after the outer atmosphere has been shed is less than 1.4 solar masses, it shrinks to a relatively tiny object (about the size of Earth) that is not massive enough for further compression to take place, known as a white dwarf.[71] The electron-degenerate matter inside a white dwarf is no longer a plasma, even though stars are generally referred to as being spheres of plasma. White dwarfs will eventually fade into black dwarfs over a very long stretch of time.

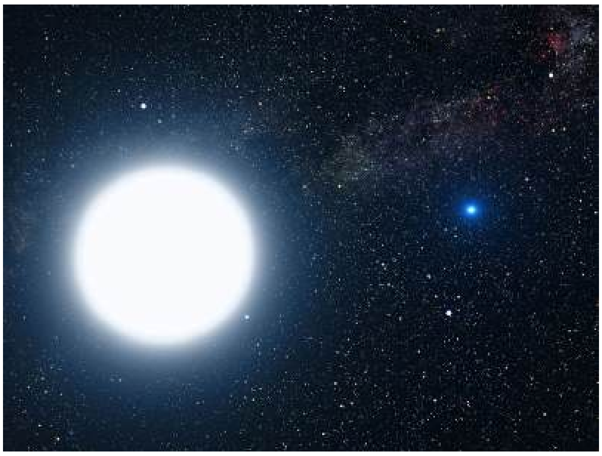

The Crab Nebula, remnants of a supernova that was first observed around 1050 AD

In larger stars, fusion continues until the iron core has grown so large (more than 1.4 solar masses) that it can no longer support its own mass. This core will suddenly collapse as its electrons are driven into its protons, forming neutrons and neutrinos in a burst of inverse beta decay, or electron capture. The shockwave formed by this sudden collapse causes the rest of the star to explode in a supernova. Supernovae are so bright that they may briefly outshine the star's entire home galaxy. When they occur within the Milky Way, supernovae have historically been observed by naked-eye observers as "new stars" where none existed before.[72]

Most of the matter in the star is blown away by the supernova explosion (forming nebulae such as the Crab Nebula[72]) and what remains will be a neutron star (which sometimes manifests itself as a pulsar or X-ray burster) or, in the case of the largest stars (large enough to leave a stellar remnant greater than roughly 4 solar masses), a black hole.[73] In a neutron star the matter is in a state known as neutron-degenerate matter, with a more exotic form of degenerate matter, QCD matter, possibly present in the core. Within a black hole the matter is in a state that is not currently understood.

The blown-off outer layers of dying stars include heavy elements which may be recycled during new star formation. These heavy elements allow the formation of rocky planets. The outflow from supernovae and the stellar wind of large stars play an important part in shaping the interstellar medium.[72]

Distribution



A white dwarf star in orbit around Sirius (artist's impression). *NASA image*

In addition to isolated stars, a multi-star system can consist of two or more gravitationally bound stars that orbit around each other. The most common multi-star system is a binary star, but systems of three or more stars are also found. For reasons of orbital stability, such multi-star systems are often organized into hierarchical sets of co-orbiting binary stars.[74] Larger groups called star clusters also exist. These range from loose stellar associations with only a few stars, up to enormous globular clusters with hundreds of thousands of stars.

It has been a long-held assumption that the majority of stars occur in gravitationally bound, multiple-star systems. This is particularly true for very massive O and B class stars, where 80% of the systems are believed to be multiple. However the portion of single star systems increases for smaller stars, so that only 25% of red dwarfs are known to have stellar companions. As 85% of all stars are red dwarfs, most stars in the Milky Way are likely single from birth.[75]

Stars are not spread uniformly across the universe, but are normally grouped into galaxies along with interstellar gas and dust. A typical galaxy contains hundreds of billions of stars, and there are more than 100 billion (10^{11}) galaxies in the observable universe.[76] While it is often believed that stars only exist within galaxies, intergalactic stars have been discovered.[77] As of 2003, astronomers estimated that there are at least 70 sextillion (7×10^{22}) stars in the observable universe.[78] However, a 2010 estimate revised the star count upward to 300 sextillion (3×10^{23}).[79]

The nearest star to the Earth, apart from the Sun, is Proxima Centauri, which is 39.9 trillion kilometres, or 4.2 light-years away. Light from Proxima Centauri takes 4.2 years to reach Earth. Travelling at the orbital speed of the Space Shuttle (8 kilometres per second—almost 30,000 kilometres per hour), it would take about 150,000 years to get there.[80] Distances like this are typical inside galactic discs, including in the vicinity of the solar system.[81] Stars can be much closer to each other in the centres of galaxies and in globular clusters, or much farther apart in galactic halos.

Due to the relatively vast distances between stars outside the galactic nucleus, collisions between stars are thought to be rare. In denser regions such as the core of globular clusters or the galactic center, collisions can be more common.[82] Such collisions can produce what are known as blue stragglers. These abnormal stars have a higher surface temperature than the other main sequence stars with the same luminosity in the cluster .[83]

Characteristics


The Sun is the nearest star to Earth.

Almost everything about a star is determined by its initial mass, including essential characteristics such as luminosity and size, as well as the star's evolution, lifespan, and eventual fate.

Age

Most stars are between 1 billion and 10 billion years old. Some stars may even be close to 13.7 billion years old—the observed age of the universe. The oldest star yet discovered, HE 1523-0901, is an estimated 13.2 billion years old.[84] [85]

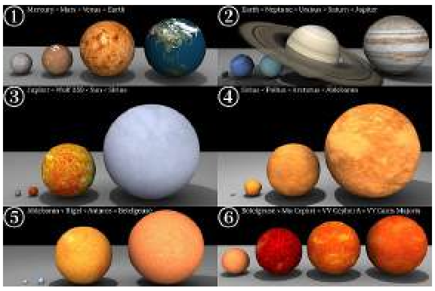
The more massive the star, the shorter its lifespan, primarily because massive stars have greater pressure on their cores, causing them to burn hydrogen more rapidly. The most massive stars last an average of about one million years, while stars of minimum mass (red dwarfs) burn their fuel very slowly and last tens to hundreds of billions of years.[86] [87]

Chemical composition

When stars form in the present Milky Way galaxy they are composed of about 71% hydrogen and 27% helium,[88] as measured by mass, with a small fraction of heavier elements. Typically the portion of heavy elements is measured in terms of the iron content of the stellar atmosphere, as iron is a common element and its absorption lines are relatively easy to measure. Because the molecular clouds where stars form are steadily enriched by heavier elements from supernovae explosions, a measurement of the chemical composition of a star can be used to infer its age.[89] The portion of heavier elements may also be an indicator of the likelihood that the star has a planetary system.[90]

The star with the lowest iron content ever measured is the dwarf HE1327-2326, with only 1/200,000th the iron content of the Sun.[91] By contrast, the super-metal-rich star μ Leonis has nearly double the abundance of iron as the Sun, while the planet-bearing star 14 Herculis has nearly triple the iron.[92] There also exist chemically peculiar stars that show unusual abundances of certain elements in their spectrum; especially chromium and rare earth elements.[93]

Diameter


Stars vary widely in size. In each image in the sequence, the right-most object appears as the left-most object in the next panel. The Earth appears at right in panel 1 and the Sun is second from the right in panel 3.

Due to their great distance from the Earth, all stars except the Sun appear to the human eye as shining points in the night sky that twinkle because of the effect of the Earth's atmosphere. The Sun is also a star, but it is close enough to the Earth to appear as a disk instead, and to provide daylight. Other than the Sun, the star with the largest apparent size is R Doradus, with an angular diameter of only 0.057 arcseconds.[94]

The disks of most stars are much too small in angular size to be observed with current ground-based optical telescopes, and so interferometer telescopes are required in order to produce images of these objects. Another technique for measuring the angular size of stars is through occultation. By precisely measuring the drop in brightness of a star as it is occulted by the Moon (or the rise in brightness when it reappears), the star's angular diameter can be computed.[95]

Stars range in size from neutron stars, which vary anywhere from 20 to 40 km in diameter, to supergiants like Betelgeuse in the Orion constellation, which has a diameter approximately 650 times larger than the Sun—about 0.9 billion kilometres. However, Betelgeuse has a much lower density than the Sun.[96]

Kinematics

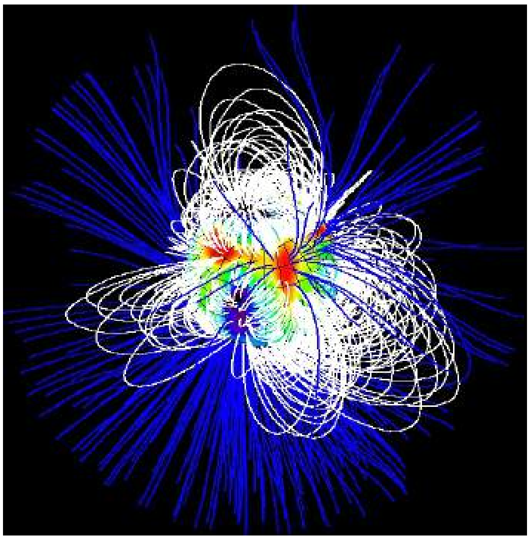
The motion of a star relative to the Sun can provide useful information about the origin and age of a star, as well as the structure and evolution of the surrounding galaxy. The components of motion of a star consist of the radial velocity toward or away from the Sun, and the traverse angular movement, which is called its proper motion.

The Pleiades, an open cluster of stars in the constellation of Taurus. These stars share a common motion through space.[97] *NASA photo*

Radial velocity is measured by the doppler shift of the star's spectral lines, and is given in units of km/s. The proper motion of a star is determined by precise astrometric measurements in units of milli-arc seconds (mas) per year. By determining the parallax of a star, the proper motion can then be converted into units of velocity. Stars with high rates of proper motion are likely to be relatively close to the Sun, making them good candidates for parallax measurements.[98]

Once both rates of movement are known, the space velocity of the star relative to the Sun or the galaxy can be computed. Among nearby stars, it has been found that population I stars have generally lower velocities than older, population II stars. The latter have elliptical orbits that are inclined to the plane of the galaxy.[99] Comparison of the kinematics of nearby stars has also led to the identification of stellar associations. These are most likely groups of stars that share a common point of origin in giant molecular clouds. [100]

Magnetic field


Surface magnetic field of SU Aur (a young star of T Tauri type), reconstructed by means of Zeeman-Doppler imaging

The magnetic field of a star is generated within regions of the interior where convective circulation occurs. This movement of conductive plasma functions like a dynamo, generating magnetic fields that extend throughout the star. The strength of the magnetic field varies with the mass and composition of the star, and the amount of magnetic surface activity depends upon the star's rate of rotation. This surface activity produces starspots, which are regions of strong magnetic fields and lower than normal surface temperatures. Coronal loops are arching magnetic fields that reach out into the corona from active regions. Stellar flares are bursts of high-energy particles that are emitted due to the same magnetic activity.[101]

Young, rapidly rotating stars tend to have high levels of surface activity because of their magnetic field. The magnetic field can act upon a star's stellar wind, however, functioning as a brake to gradually slow the rate of rotation as the star grows older. Thus, older stars such as the Sun have a much slower rate of rotation and a lower level of surface activity. The activity levels of slowly rotating stars tend to vary in a cyclical manner and can shut down altogether for periods.[102] During the Maunder minimum, for example, the Sun underwent a 70-year period with almost no sunspot activity.

Mass

One of the most massive stars known is Eta Carinae,[103] with 100–150 times as much mass as the Sun; its lifespan is very short—only several million years at most. A study of the Arches cluster suggests that 150 solar masses is the upper limit for stars in the current era of the universe.[104] The reason for this limit is not precisely known, but it is partially due to the Eddington luminosity which defines the maximum amount of luminosity that can pass through the atmosphere of a star without ejecting the gases into space. However, a star named R136a1 in the RMC 136a star cluster has been measured at 265 solar masses, putting this limit into question.[105]

The first stars to form after the Big Bang may have been larger, up to 300 solar masses or more,[106] due to the complete absence of elements heavier than lithium in their composition. This generation of supermassive, population III stars is long extinct, however, and currently only theoretical.

The reflection nebula NGC 1999 is brilliantly illuminated by V380 Orionis (center), a variable star with about 3.5 times the mass of the Sun. The black patch of sky is a vast hole of empty space and not a dark nebula as previously thought. *NASA image*

With a mass only 93 times that of Jupiter, AB Doradus C, a companion to AB Doradus A, is the smallest known star undergoing nuclear fusion in its core.[107] For stars with similar metallicity to the Sun, the theoretical minimum mass the star can have, and still undergo fusion at the core, is estimated to be about 75 times the mass of Jupiter.[108] [109] When the metallicity is very low, however, a recent study of the faintest stars found that the minimum star size seems to be about 8.3% of the solar mass, or about 87 times the mass of Jupiter.[109] [110] Smaller bodies are called brown dwarfs, which occupy a poorly defined grey area between stars and gas giants.

The combination of the radius and the mass of a star determines the surface gravity. Giant stars have a much lower surface gravity than main sequence stars, while the opposite is the case for degenerate, compact stars such as white dwarfs. The surface gravity can influence the appearance of a star's spectrum, with higher gravity causing a broadening of the absorption lines.[32]

Stars are sometimes grouped by mass based upon their evolutionary behavior as they approach the end of their nuclear fusion lifetimes. *Very low mass stars* with masses below 0.5 solar masses do not enter the asymptotic giant branch (AGB) but evolve directly into white dwarfs. *Low mass stars* with a mass below about 1.8–2.2 solar masses (depending on composition) do enter the AGB, where they develop a degenerate helium core. *Intermediate-mass stars* undergo helium fusion and develop a degenerate carbon-oxygen core. *Massive stars* have a minimum mass of 7–10 solar masses, but this may be as low as 5–6 solar masses. These stars undergo carbon fusion, with their lives ending in a core-collapse supernova explosion.[111]

Rotation

The rotation rate of stars can be approximated through spectroscopic measurement, or more exactly determined by tracking the rotation rate of starspots. Young stars can have a rapid rate of rotation greater than 100 km/s at the equator. The B-class star Achernar, for example, has an equatorial rotation velocity of about 225 km/s or greater, giving it an equatorial diameter that is more than 50% larger than the distance between the poles. This rate of rotation is just below the critical velocity of 300 km/s where the star would break apart.[112] By contrast, the Sun only rotates once every 25 – 35 days, with an equatorial velocity of 1.994 km/s. The star's magnetic field and the stellar wind serve to slow down a main sequence star's rate of rotation by a significant amount as it evolves on the main sequence.[113]

Degenerate stars have contracted into a compact mass, resulting in a rapid rate of rotation. However they have relatively low rates of rotation compared to what would be expected by conservation of angular momentum—the tendency of a rotating body to compensate for a contraction in size by increasing its rate of spin. A large portion of the star's angular momentum is dissipated as a result of mass loss through the stellar wind.[114] In spite of this, the rate of rotation for a pulsar can be very rapid. The pulsar at the heart of the Crab nebula, for example, rotates 30 times per second.[115] The rotation rate of the pulsar will gradually slow due to the emission of radiation.

Temperature

The surface temperature of a main sequence star is determined by the rate of energy production at the core and the radius of the star and is often estimated from the star's color index.[116] It is normally given as the effective temperature, which is the temperature of an idealized black body that radiates its energy at the same luminosity per surface area as the star. Note that the effective temperature is only a representative value, however, as stars actually have a temperature gradient that decreases with increasing distance from the core.[117] The temperature in the core region of a star is several million kelvins.[118]

The stellar temperature will determine the rate of energization or ionization of different elements, resulting in characteristic absorption lines in the spectrum. The surface temperature of a star, along with its visual absolute magnitude and absorption features, is used to classify a star (see classification below).[32]

Massive main sequence stars can have surface temperatures of 50,000 K. Smaller stars such as the Sun have surface temperatures of a few thousand K. Red giants have relatively low surface temperatures of about 3,600 K, but they also have a high luminosity due to their large exterior surface area.[119]

Radiation

The energy produced by stars, as a by-product of nuclear fusion, radiates into space as both electromagnetic radiation and particle radiation. The particle radiation emitted by a star is manifested as the stellar wind[120] (which exists as a steady stream of electrically charged particles, such as free protons, alpha particles, and beta particles, emanating from the star’s outer layers) and as a steady stream of neutrinos emanating from the star’s core.

The production of energy at the core is the reason why stars shine so brightly: every time two or more atomic nuclei of one element fuse together to form an atomic nucleus of a new heavier element, gamma ray photons are released from the nuclear fusion reaction. This energy is converted to other forms of electromagnetic energy, including visible light, by the time it reaches the star’s outer layers.

The color of a star, as determined by the peak frequency of the visible light, depends on the temperature of the star’s outer layers, including its photosphere.[121] Besides visible light, stars also emit forms of electromagnetic radiation that are invisible to the human eye. In fact, stellar electromagnetic radiation spans the entire electromagnetic spectrum, from the longest wavelengths of radio waves and infrared to the shortest wavelengths of ultraviolet, X-rays, and gamma rays. All components of stellar electromagnetic radiation, both visible and invisible, are typically significant.

Using the stellar spectrum, astronomers can also determine the surface temperature, surface gravity, metallicity and rotational velocity of a star. If the distance of the star is known, such as by measuring the parallax, then the luminosity of the star can be derived. The mass, radius, surface gravity, and rotation period can then be estimated based on stellar models. (Mass can be measured directly for stars in binary systems. The technique of gravitational microlensing will also yield the mass of a star.[122]) With these parameters, astronomers can also estimate the age of the star.[123]

Luminosity

In astronomy, luminosity is the amount of light, and other forms of radiant energy, a star radiates per unit of time. The luminosity of a star is determined by the radius and the surface temperature. However, many stars do not radiate a uniform flux—the amount of energy radiated per unit area—across their entire surface. The rapidly rotating star Vega, for example, has a higher energy flux at its poles than along its equator.[124]

Surface patches with a lower temperature and luminosity than average are known as starspots. Small, *dwarf* stars such as the Sun generally have essentially featureless disks with only small starspots. Larger, *giant* stars have much bigger, much more obvious starspots,[125] and they also exhibit strong stellar limb darkening. That is, the brightness decreases towards the edge of the stellar disk.[126] Red dwarf flare stars such as UV Ceti may also possess prominent starspot features.[127]

Magnitude

The apparent brightness of a star is measured by its apparent magnitude, which is the brightness of a star with respect to the star's luminosity, distance from Earth, and the altering of the star's light as it passes through Earth's atmosphere. Intrinsic or absolute magnitude is directly related to a star's luminosity and is what the apparent magnitude a star would be if the distance between the Earth and the star were 10 parsecs (32.6 light-years).

Number of stars brighter than magnitude

Apparent magnitude	**Number of Stars**[128]
0	4
1	15
2	48
3	171
4	513
5	1,602
6	4,800
7	14,000

Both the apparent and absolute magnitude scales are logarithmic units: one whole number difference in magnitude is equal to a brightness variation of about 2.5 times[129] (the 5th root of 100 or approximately 2.512). This means that a first magnitude (+1.00) star is about 2.5 times brighter than a second magnitude (+2.00) star, and approximately 100 times brighter than a sixth magnitude (+6.00) star. The faintest stars visible to the naked eye under good seeing conditions are about magnitude +6.

On both apparent and absolute magnitude scales, the smaller the magnitude number, the brighter the star; the larger the magnitude number, the fainter. The brightest stars, on either scale, have negative magnitude numbers. The variation in brightness (ΔL) between two stars is calculated by subtracting the magnitude number of the brighter star (m_b) from the magnitude number of the fainter star (m_f), then using the difference as an exponent for the base number 2.512; that is to say:

$$\Delta m = m_{\mathrm{f}} - m_{\mathrm{b}}$$

$$2.512^{\Delta m} = \Delta L$$

Relative to both luminosity and distance from Earth, absolute magnitude (M) and apparent magnitude (m) are not equivalent for an individual star;[129] for example, the bright star Sirius has an apparent magnitude of −1.44, but it has an absolute magnitude of +1.41.

The Sun has an apparent magnitude of −26.7, but its absolute magnitude is only +4.83. Sirius, the brightest star in the night sky as seen from Earth, is approximately 23 times more luminous than the Sun, while Canopus, the second brightest star in the night sky with an absolute magnitude of −5.53, is approximately 14,000 times more luminous than the Sun. Despite Canopus being vastly more luminous than Sirius, however, Sirius appears brighter than Canopus. This is because Sirius is merely 8.6 light-years from the Earth, while Canopus is much farther away at a distance of 310 light-years.

As of 2006, the star with the highest known absolute magnitude is LBV 1806-20, with a magnitude of −14.2. This star is at least 5,000,000 times more luminous than the Sun.[130] The least luminous stars that are currently known are located in the NGC 6397 cluster. The faintest red dwarfs in the cluster were magnitude 26, while a 28th magnitude white dwarf was also discovered. These faint stars are so dim that their light is as bright as a birthday candle on the Moon when viewed from the Earth.[131]

Classification

Surface Temperature Ranges for Different Stellar Classes[132]

Class	Temperature	Sample star
O	33,000 K or more	Zeta Ophiuchi
B	10,500–30,000 K	Rigel
A	7,500–10,000 K	Altair
F	6,000–7,200 K	Procyon A
G	5,500–6,000 K	Sun
K	4,000–5,250 K	Epsilon Indi
M	2,600–3,850 K	Proxima Centauri

The current stellar classification system originated in the early 20th century, when stars were classified from *A* to *Q* based on the strength of the hydrogen line.[133] It was not known at the time that the major influence on the line strength was temperature; the hydrogen line strength reaches a peak at over 9000 K, and is weaker at both hotter and cooler temperatures. When the classifications were reordered by temperature, it more closely resembled the modern scheme.[134]

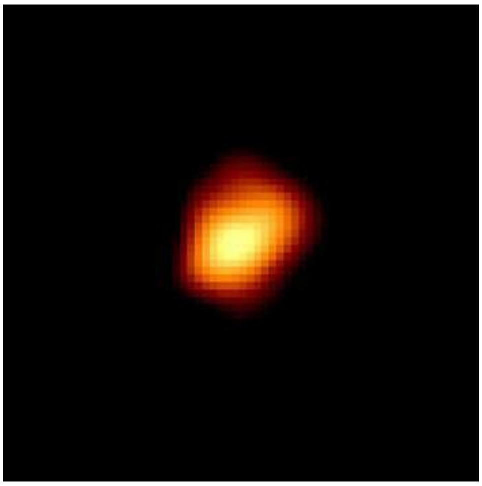
There are different single-letter classifications of stars according to their spectra, ranging from type *O*, which are very hot, to *M*, which are so cool that molecules may form in their atmospheres. The main classifications in order of decreasing surface temperature are: *O, B, A, F, G, K*, and *M*. A variety of rare spectral types have special classifications. The most common of these are types *L* and *T*, which classify the coldest low-mass stars and brown dwarfs. Each letter has 10 sub-divisions, numbered from 0 to 9, in order of decreasing temperature. However, this system breaks down at extreme high temperatures: class *O0* and *O1* stars may not exist.[135]

In addition, stars may be classified by the luminosity effects found in their spectral lines, which correspond to their spatial size and is determined by the surface gravity. These range from *0* (hypergiants) through *III* (giants) to *V* (main sequence dwarfs); some authors add *VII* (white dwarfs). Most stars belong to the main sequence, which consists of ordinary hydrogen-burning stars. These fall along a narrow, diagonal band when graphed according to their absolute magnitude and spectral type.[135] Our Sun is a main sequence *G2V* yellow dwarf, being of intermediate temperature and ordinary size.

Additional nomenclature, in the form of lower-case letters, can follow the spectral type to indicate peculiar features of the spectrum. For example, an "*e*" can indicate the presence of emission lines; "*m*" represents unusually strong levels of metals, and "*var*" can mean variations in the spectral type.[135]

White dwarf stars have their own class that begins with the letter *D*. This is further sub-divided into the classes *DA*, *DB*, *DC*, *DO*, *DZ*, and *DQ*, depending on the types of prominent lines found in the spectrum. This is followed by a numerical value that indicates the temperature index.[136]

Variable stars



The asymmetrical appearance of Mira, an oscillating variable star. *NASA HST image*

Variable stars have periodic or random changes in luminosity because of intrinsic or extrinsic properties. Of the intrinsically variable stars, the primary types can be subdivided into three principal groups.

During their stellar evolution, some stars pass through phases where they can become pulsating variables. Pulsating variable stars vary in radius and luminosity over time, expanding and contracting with periods ranging from minutes to years, depending on the size of the star. This category includes Cepheid and cepheid-like stars, and long-period variables such as Mira.[137]

Eruptive variables are stars that experience sudden increases in luminosity because of flares or mass ejection events.[137] This group includes protostars, Wolf-Rayet stars, and Flare stars, as well as giant and supergiant stars.

Cataclysmic or explosive variables undergo a dramatic change in their properties. This group includes novae and supernovae. A binary star system that includes a nearby white dwarf can produce certain types of these spectacular stellar explosions, including the nova and a Type 1a supernova.[4] The explosion is created when the white dwarf accretes hydrogen from the companion star, building up mass until the hydrogen undergoes fusion.[138] Some novae are also recurrent, having periodic outbursts of moderate amplitude.[137]

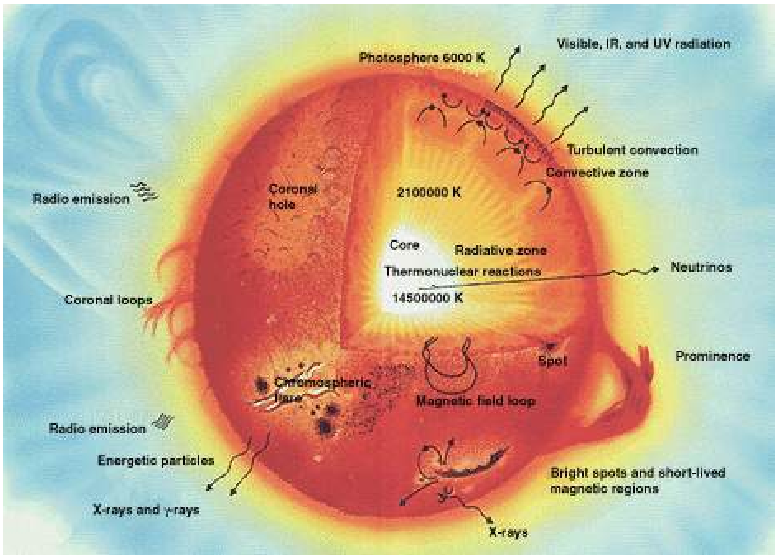
Stars can also vary in luminosity because of extrinsic factors, such as eclipsing binaries, as well as rotating stars that produce extreme starspots.[137] A notable example of an eclipsing binary is Algol, which regularly varies in magnitude from 2.3 to 3.5 over a period of 2.87 days.

Structure

The interior of a stable star is in a state of hydrostatic equilibrium: the forces on any small volume almost exactly counterbalance each other. The balanced forces are inward gravitational force and an outward force due to the pressure gradient within the star. The pressure gradient is established by the temperature gradient of the plasma; the outer part of the star is cooler than the core. The temperature at the core of a main sequence or giant star is at least on the order of 10^7 K. The resulting temperature and pressure at the hydrogen-burning core of a main sequence star are sufficient for nuclear fusion to occur and for sufficient energy to be produced to prevent further collapse of the star.[139] [140]

As atomic nuclei are fused in the core, they emit energy in the form of gamma rays. These photons interact with the surrounding plasma, adding to the thermal energy at the core. Stars on the main sequence convert hydrogen into helium, creating a slowly but steadily increasing proportion of helium in the core. Eventually the helium content becomes predominant and energy production ceases at the core. Instead, for stars of more than 0.4 solar masses, fusion occurs in a slowly expanding shell around the degenerate helium core.[141]

In addition to hydrostatic equilibrium, the interior of a stable star will also maintain an energy balance of thermal equilibrium. There is a radial temperature gradient throughout the interior that results in a flux of energy flowing toward the exterior. The outgoing flux of energy leaving any layer within the star will exactly match the incoming flux from below.



This diagram shows a cross-section of a solar-type star. *NASA image*

The radiation zone is the region within the stellar interior where radiative transfer is sufficiently efficient to maintain the flux of energy. In this region the plasma will not be perturbed and any mass motions will die out. If this is not the case, however, then the plasma becomes unstable and convection will occur, forming a convection zone. This can occur, for example, in regions where very high energy fluxes occur, such as near the core or in areas with high opacity as in the outer envelope.[140]

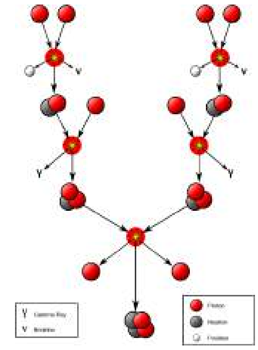
The occurrence of convection in the outer envelope of a main sequence star depends on the mass. Stars with several times the mass of the Sun have a convection zone deep within the interior and a radiative zone in the outer layers. Smaller stars such as the Sun are just the opposite, with the convective zone located in the outer layers.[142] Red dwarf stars with less than 0.4 solar masses are convective throughout, which prevents the accumulation of a helium core.[2] For most stars the convective zones will also vary over time as the star ages and the constitution of the interior is modified.[140]

The portion of a star that is visible to an observer is called the photosphere. This is the layer at which the plasma of the star becomes transparent to photons of light. From here, the energy generated at the core becomes free to propagate out into space. It is within the photosphere that sun spots, or regions of lower than average temperature, appear.

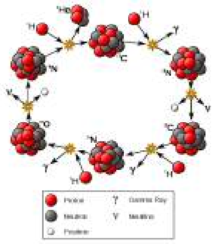
Above the level of the photosphere is the stellar atmosphere. In a main sequence star such as the Sun, the lowest level of the atmosphere is the thin chromosphere region, where spicules appear and stellar flares begin. This is surrounded by a transition region, where the temperature rapidly increases within a distance of only 100 km. Beyond this is the corona, a volume of super-heated plasma that can extend outward to several million kilometres.[143] The existence of a corona appears to be dependent on a convective zone in the outer layers of the star.[142] Despite its high temperature, the corona emits very little light. The corona region of the Sun is normally only visible during a solar eclipse.

From the corona, a stellar wind of plasma particles expands outward from the star, propagating until it interacts with the interstellar medium. For the Sun, the influence of its solar wind extends throughout the bubble-shaped region of the heliosphere.[144]

Nuclear fusion reaction pathways



Overview of the proton-proton chain



The carbon-nitrogen-oxygen cycle

A variety of different nuclear fusion reactions take place inside the cores of stars, depending upon their mass and composition, as part of stellar nucleosynthesis. The net mass of the fused atomic nuclei is smaller than the sum of the constituents. This lost mass is released as electromagnetic energy, according to the mass-energy equivalence relationship $E = mc^2$.[1]

The hydrogen fusion process is temperature-sensitive, so a moderate increase in the core temperature will result in a significant increase in the fusion rate. As a result the core temperature of main sequence stars only varies from 4 million kelvin for a small M-class star to 40 million kelvin for a massive O-class star.[118]

In the Sun, with a 10-million-kelvin core, hydrogen fuses to form helium in the proton-proton chain reaction:[145]

$4\,^1\text{H} \rightarrow 2\,^2\text{H} + 2e^+ + 2\nu_e$ (4.0 MeV + 1.0 MeV)

$2\,^1\text{H} + 2\,^2\text{H} \rightarrow 2\,^3\text{He} + 2\gamma$ (5.5 MeV)

$2\,^3\text{He} \rightarrow {}^4\text{He} + 2\,^1\text{H}$ (12.9 MeV)

These reactions result in the overall reaction:

$4\,^1\text{H} \rightarrow {}^4\text{He} + 2e^+ + 2\gamma + 2\nu_e$ (26.7 MeV)

where e^+ is a positron, γ is a gamma ray photon, ν_e is a neutrino, and H and He are isotopes of hydrogen and helium, respectively. The energy released by this reaction is in millions of electron volts, which is actually only a tiny amount of energy. However enormous numbers of these reactions occur constantly, producing all the energy necessary to sustain the star's radiation output.

Minimum stellar mass required for fusion

Element	Solar masses
Hydrogen	0.01
Helium	0.4
Carbon	5[146]
Neon	8

In more massive stars, helium is produced in a cycle of reactions catalyzed by carbon—the carbon-nitrogen-oxygen cycle.[145]

In evolved stars with cores at 100 million kelvin and masses between 0.5 and 10 solar masses, helium can be transformed into carbon in the triple-alpha process that uses the intermediate element beryllium:[145]

$^{4}He + {}^{4}He + 92\ keV \rightarrow {}^{8*}Be$

$^{4}He + {}^{8*}Be + 67\ keV \rightarrow {}^{12*}C$

$^{12*}C \rightarrow {}^{12}C + \gamma + 7.4\ MeV$

For an overall reaction of:

$3\,^{4}He \rightarrow {}^{12}C + \gamma + 7.2\ MeV$

In massive stars, heavier elements can also be burned in a contracting core through the neon burning process and oxygen burning process. The final stage in the stellar nucleosynthesis process is the silicon burning process that results in the production of the stable isotope iron-56. Fusion can not proceed any further except through an endothermic process, and so further energy can only be produced through gravitational collapse.[145]

The example below shows the amount of time required for a star of 20 solar masses to consume all of its nuclear fuel. As an O-class main sequence star, it would be 8 times the solar radius and 62,000 times the Sun's luminosity.[147]

Fuel material	Temperature (million kelvins)	Density (kg/cm^3)	Burn duration (τ in years)
H	37	0.0045	8.1 million
He	188	0.97	1.2 million
C	870	170	976
Ne	1,570	3,100	0.6
O	1,980	5,550	1.25
S/Si	3,340	33,400	0.0315[148]

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Galactic astronomy

Galactic astronomy is the study of our own Milky Way galaxy and all its contents. This is in contrast to extragalactic astronomy, which is the study of everything outside our galaxy, including all other galaxies.

Galactic astronomy should not be confused with galaxy formation and evolution, which is the general study of galaxies, their formation, structure, components, dynamics, interactions, and the range of forms they take.

Our own Milky Way galaxy, where our solar system belongs, is in many ways the best studied galaxy, although important parts of it are obscured from view in visible wavelengths by regions of cosmic dust. The development of radio astronomy, infrared astronomy and submillimeter astronomy in the 20th Century allowed the gas and dust of the Milky Way to be mapped for the first time.

Subcategories

A standard set of subcategories is used by astronomical journals to split up the subject of Galactic Astronomy:

1. abundances - the study of the location of elements heavier than helium
2. bulge - the study of the bulge around the center of the Milky Way
3. center - the study of the central region of the Milky Way
4. disk - the study of the Milky Way disk (the plane upon which most galactic objects are aligned)
5. evolution - the evolution of the Milky Way
6. formation - the formation of the Milky Way
7. fundamental parameters - the fundamental parameters of the Milky Way (mass, size etc)
8. globular clusters - globular clusters within the Milky Way
9. halo - the large halo around the Milky Way
10. kinematics and dynamics - the motions of stars and clusters
11. nucleus - the region around the black hole at the center of the Milky Way (Sagittarius A*)
12. open clusters and associations - open clusters and associations of stars
13. solar neighbourhood - nearby stars
14. stellar content - numbers and types of stars in the Milky Way
15. structure - the structure (spiral arms etc)

Stellar populations

- Globular clusters
- Open clusters

Interstellar medium

- Interplanetary space - Interplanetary medium - interplanetary dust
- Interstellar space - Interstellar medium - interstellar dust
- Intergalactic space - Intergalactic medium - Intergalactic dust

External links

- Mapping the hydrogen gas in the Milky Way [1]
- Mapping the dust in the centre of the Milky Way [2]
- Search for Astronomy [3]

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Extragalactic astronomy

Extragalactic astronomy is the branch of astronomy concerned with objects outside our own Milky Way Galaxy. In other words, it is the study of all astronomical objects which are not covered by galactic astronomy.

As instrumentation has improved, more distant objects can now be examined in detail. It is therefore useful to sub-divide this branch into **Near-Extragalactic Astronomy** and **Far-Extragalactic Astronomy**. The former deals with objects such as the galaxies of our Local Group, which are close enough to allow very detailed analyses of their contents (e.g. supernova remnants, stellar associations). The latter describes the study of objects sufficiently far away that only the brightest phenomena are observable.

Some topics include:

- Groups and clusters of galaxies
- Quasars
- Radio galaxies
- Supernovae
- Intergalactic stars
- Intergalactic dust[1]
- Intergalactic dust clouds[1]

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Physical cosmology

Physical cosmology, as a branch of astronomy, is the study of the largest-scale structures and dynamics of the universe and is concerned with fundamental questions about its formation and evolution.[1] For most of human history, it was a branch of metaphysics and religion. Cosmology as a science originated with the Copernican principle, which implies that celestial bodies obey identical physical laws to those on Earth, and Newtonian mechanics, which first allowed us to understand those laws.

Physical cosmology, as it is now understood, began with the twentieth century development of Albert Einstein's general theory of relativity and better astronomical observations of extremely distant objects. These advances made it possible to speculate about the origin of the universe, and allowed scientists to establish the Big Bang Theory as the leading cosmological model. Some researchers still advocate a handful of alternative cosmologies; however, cosmologists generally agree that the Big Bang theory best explains observations.

Cosmology draws heavily on the work of many disparate areas of research in physics. Areas relevant to cosmology include particle physics experiments and theory, including string theory, astrophysics, general relativity, and plasma physics. Thus, cosmology unites the physics of the largest structures in the universe with the physics of the smallest structures in the universe.

History of physical cosmology

Modern cosmology developed along tandem tracks of theory and observation. In 1915, Albert Einstein formulated his theory of general relativity, which provided a unified description of gravity as a geometric property of space and time. At the time, physicists believed in a perfectly static universe that had no beginning or end. Einstein added a cosmological constant to his theory in order to force it to model a static universe containing matter. This so-called *Einstein universe* is, however, unstable; it will eventually start expanding or contracting. The cosmological solutions of general relativity were found by Alexander Friedmann, whose equations describe the Friedmann-Lemaître-Robertson-Walker universe, which may expand or contract.

In the 1910s, Vesto Slipher (and later Carl Wilhelm Wirtz) interpreted the red shift of spiral nebulae as a Doppler shift that indicated they were receding from Earth. However, it is difficult to determine the distance to astronomical objects. One way is to compare the physical size of an object to its angular size, but a physical size must be assumed to do this. Another method is to measure the brightness of an object and assume an intrinsic luminosity, from which the distance may be determined using the inverse square law. Due to the difficulty of using these methods, they did not realize that the nebulae were actually galaxies outside our own Milky Way, nor did they speculate about the cosmological implications. In 1927, the Belgian Roman Catholic priest Georges Lemaître independently derived the Friedmann-Lemaître-Robertson-Walker equations and proposed, on the basis of the recession of spiral nebulae, that the universe began with the "explosion" of a "primeval atom"—which was later called the Big Bang. In 1929, Edwin Hubble provided an observational basis for Lemaître's theory. Hubble showed that the spiral nebulae were galaxies by determining their distances using measurements of the brightness of Cepheid variable stars. He discovered a relationship between the redshift of a galaxy and its distance. He interpreted this as evidence that the galaxies are receding from Earth in every direction at speeds directly proportional to their distance. This fact is now known as Hubble's law, though the numerical factor Hubble found relating recessional velocity and distance was off by a factor of ten, due to not knowing at the time about different types of Cepheid variables.

Given the cosmological principle, Hubble's law suggested that the universe was expanding. There were two primary explanations put forth for the expansion of the universe. One was Lemaître's Big Bang theory, advocated and developed by George Gamow. The other possibility was Fred Hoyle's steady state model in which new matter would be created as the galaxies moved away from each other. In this model, the universe is roughly the same at any point in time.

For a number of years the support for these theories was evenly divided. However, the observational evidence began to support the idea that the universe evolved from a hot dense state. The discovery of the cosmic microwave background in 1965 lent strong support to the Big Bang model, and since the precise measurements of the cosmic microwave background by the Cosmic Background Explorer in the early 1990s, few cosmologists have seriously proposed other theories of the origin and evolution of the cosmos. One consequence of this is that in standard general relativity, the universe began with a singularity, as demonstrated by Stephen Hawking and Roger Penrose in the 1960s.

History of the Universe

The history of the universe is a central issue in cosmology. The history of the universe is divided into different periods called epochs, according to the dominant forces and processes in each period. The standard cosmological model is known as the ΛCDM model.

Equations of motion

The equations of motion governing the universe as a whole are derived from general relativity with a small, positive cosmological constant[2] . The solution is an expanding universe; due to this expansion the radiation and matter in the universe are cooled down and become diluted. At first, the expansion is slowed down by gravitation due to the radiation and matter content of the universe. However, as these become diluted, the cosmological constant becomes more dominant and the expansion of the universe starts to accelerate rather than decelerate. In our universe this has already happened, billions of years ago.

Particle physics in cosmology

Particle physics is important to the behavior of the early universe, since the early universe was so hot that the average energy density was very high. Because of this, scattering processes and decay of unstable particles are important in cosmology.

As a rule of thumb, a scattering or a decay process is cosmologically important in a certain cosmological epoch if the time scale describing that process is smaller or comparable to the time scale of the expansion of the universe, which is $1/H$ with H being the Hubble constant at that time. This is roughly equal to the age of the universe at that time.

Timeline of the Big Bang

Observations suggest that the universe began around 13.7 billion years ago. Since then, the evolution of the universe has passed through three phases. The very early universe, which is still poorly understood, was the split second in which the universe was so hot that particles had energies higher than those currently accessible in particle accelerators on Earth. Therefore, while the basic features of this epoch have been worked out in the Big Bang theory, the details are largely based on educated guesses. Following this, in the early universe, the evolution of the universe proceeded according to known high energy physics. This is when the first protons, electrons and neutrons formed, then nuclei and finally atoms. With the formation of neutral hydrogen, the cosmic microwave background was emitted. Finally, the epoch of structure formation began, when matter started to aggregate into the first stars and quasars, and ultimately galaxies, clusters of galaxies and superclusters formed. The future of the universe is not yet firmly known, but according to the ΛCDM model it will continue expanding forever.

Areas of study

Below, some of the most active areas of inquiry in cosmology are described, in roughly chronological order. This does not include all of the Big Bang cosmology, which is presented in Timeline of the Big Bang.

The very early universe

While the early, hot universe appears to be well explained by the Big Bang from roughly 10^{-33} seconds onwards, there are several problems. One is that there is no compelling reason, using current particle physics, to expect the universe to be flat, homogeneous and isotropic (see the cosmological principle). Moreover, grand unified theories of particle physics suggest that there should be magnetic monopoles in the universe, which have not been found. These problems are resolved by a brief period of cosmic inflation, which drives the universe to flatness, smooths out anisotropies and inhomogeneities to the observed level, and exponentially dilutes the monopoles. The physical model behind cosmic inflation is extremely simple, however it has not yet been confirmed by particle physics, and there are difficult problems reconciling inflation and quantum field theory. Some cosmologists think that string theory and brane cosmology will provide an alternative to inflation.

Another major problem in cosmology is what caused the universe to contain more particles than antiparticles. Cosmologists can observationally deduce that the universe is not split into regions of matter and antimatter. If it were, there would be X-rays and gamma rays produced as a result of annihilation, but this is not observed. This problem is called the baryon asymmetry, and the theory to describe the resolution is called baryogenesis. The theory of baryogenesis was worked out by Andrei Sakharov in 1967, and requires a violation of the particle physics symmetry, called CP-symmetry, between matter and antimatter. Particle accelerators, however, measure too small a violation of CP-symmetry to account for the baryon asymmetry. Cosmologists and particle physicists are trying to find additional violations of the CP-symmetry in the early universe that might account for the baryon asymmetry.

Both the problems of baryogenesis and cosmic inflation are very closely related to particle physics, and their resolution might come from high energy theory and experiment, rather than through observations of the universe.

Big bang nucleosynthesis

Big Bang Nucleosynthesis is the theory of the formation of the elements in the early universe. It finished when the universe was about three minutes old and its temperature dropped below that at which nuclear fusion could occur. Big Bang nucleosynthesis had a brief period during which it could operate, so only the very lightest elements were produced. Starting from hydrogen ions (protons), it principally produced deuterium, helium-4 and lithium. Other elements were produced in only trace abundances. The basic theory of nucleosynthesis was developed in 1948 by George Gamow, Ralph Asher Alpher and Robert Herman. It was used for many years as a probe of physics at the time of the Big Bang, as the theory of Big Bang nucleosynthesis connects the abundances of primordial light elements with the features of the early universe. Specifically, it can be used to test the equivalence principle, to probe dark matter, and test neutrino physics. Some cosmologists have proposed that Big Bang nucleosynthesis suggests there is a fourth "sterile" species of neutrino.

Cosmic microwave background

The cosmic microwave background is radiation left over from decoupling after the epoch of recombination when neutral atoms first formed. At this point, radiation produced in the Big Bang stopped Thomson scattering from charged ions. The radiation, first observed in 1965 by Arno Penzias and Robert Woodrow Wilson, has a perfect thermal black-body spectrum. It has a temperature of 2.7 kelvins today and is isotropic to one part in 10^5. Cosmological perturbation theory, which describes the evolution of slight inhomogeneities in the early universe, has allowed cosmologists to precisely calculate the angular power spectrum of the radiation, and it has been measured by the recent satellite experiments (COBE and WMAP) and many ground and balloon-based experiments (such as Degree Angular Scale Interferometer, Cosmic Background Imager, and Boomerang). One of the goals of these efforts is to measure the basic parameters of the Lambda-CDM model with increasing accuracy, as well as to test the predictions of the Big Bang model and look for new physics. The recent measurements made by WMAP, for example, have placed limits on the neutrino masses.

Newer experiments, such as QUIET and the Atacama Cosmology Telescope, are trying to measure the polarization of the cosmic microwave background. These measurements are expected to provide further confirmation of the theory as well as information about cosmic inflation, and the so-called secondary anisotropies, such as the Sunyaev-Zel'dovich effect and Sachs-Wolfe effect, which are caused by interaction between galaxies and clusters with the cosmic microwave background.

Formation and evolution of large-scale structure

Understanding the formation and evolution of the largest and earliest structures (i.e., quasars, galaxies, clusters and superclusters) is one of the largest efforts in cosmology. Cosmologists study a model of **hierarchical structure formation** in which structures form from the bottom up, with smaller objects forming first, while the largest objects, such as superclusters, are still assembling. One way to study structure in the universe is to survey the visible galaxies, in order to construct a three-dimensional picture of the galaxies in the universe and measure the matter power spectrum. This is the approach of the Sloan Digital Sky Survey and the 2dF Galaxy Redshift Survey.

Another tool for understanding structure formation is simulations, which cosmologists use to study the gravitational aggregation of matter in the universe, as it clusters into filaments, superclusters and voids. Most simulations contain only non-baryonic cold dark matter, which should suffice to understand the universe on the largest scales, as there is much more dark matter in the universe than visible, baryonic matter. More advanced simulations are starting to include baryons and study the formation of individual galaxies. Cosmologists study these simulations to see if they agree with the galaxy surveys, and to understand any discrepancy.

Other, complementary observations to measure the distribution of matter in the distant universe and to probe reionization include:

- The Lyman alpha forest, which allows cosmologists to measure the distribution of neutral atomic hydrogen gas in the early universe, by measuring the absorption of light from distant quasars by the gas.
- The 21 centimeter absorption line of neutral atomic hydrogen also provides a sensitive test of cosmology
- Weak lensing, the distortion of a distant image by gravitational lensing due to dark matter.

These will help cosmologists settle the question of when and how structure formed in the universe.

Dark matter

Evidence from Big Bang nucleosynthesis, the cosmic microwave background and structure formation suggests that about 23% of the mass of the universe consists of non-baryonic dark matter, whereas only 4% consists of visible, baryonic matter. The gravitational effects of dark matter are well understood, as it behaves like a cold, non-radiative fluid that forms haloes around galaxies. Dark matter has never been detected in the laboratory, and the particle physics nature of dark matter remains completely unknown. Without observational constraints, there are a number of candidates, such as a stable supersymmetric particle, a weakly interacting massive particle, an axion, and a massive compact halo object. Alternatives to the dark matter hypothesis include a modification of gravity at small accelerations (MOND) or an effect from brane cosmology.

Dark energy

If the universe is flat, there must be an additional component making up 73% (in addition to the 23% dark matter and 4% baryons) of the energy density of the universe. This is called dark energy. In order not to interfere with Big Bang nucleosynthesis and the cosmic microwave background, it must not cluster in haloes like baryons and dark matter. There is strong observational evidence for dark energy, as the total energy density of the universe is known through constraints on the flatness of the universe, but the amount of clustering matter is tightly measured, and is much less than this. The case for dark energy was strengthened in 1999, when measurements demonstrated that the expansion of the universe has begun to gradually accelerate.

Apart from its density and its clustering properties, nothing is known about dark energy. Quantum field theory predicts a cosmological constant much like dark energy, but 120 orders of magnitude larger than that observed. Steven Weinberg and a number of string theorists (see string landscape) have used this as evidence for the anthropic principle, which suggests that the cosmological constant is so small because life (and thus physicists, to make observations) cannot exist in a universe with a large cosmological constant, but many people find this an unsatisfying explanation. Other possible explanations for dark energy include quintessence or a modification of gravity on the largest scales. The effect on cosmology of the dark energy that these models describe is given by the dark energy's equation of state, which varies depending upon the theory. The nature of dark energy is one of the most challenging problems in cosmology.

A better understanding of dark energy is likely to solve the problem of the ultimate fate of the universe. In the current cosmological epoch, the accelerated expansion due to dark energy is preventing structures larger than superclusters from forming. It is not known whether the acceleration will continue indefinitely, perhaps even increasing until a big rip, or whether it will eventually reverse.

Other areas of inquiry

Cosmologists also study:

- whether primordial black holes were formed in our universe, and what happened to them.
- the GZK cutoff for high-energy cosmic rays, and whether it signals a failure of special relativity at high energies
- the equivalence principle, whether or not Einstein's general theory of relativity is the correct theory of gravitation, and if the fundamental laws of physics are the same everywhere in the universe.

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Amateur astronomy

Amateur astronomy

Amateur astronomy, also called **backyard astronomy** and **stargazing**, is a hobby whose participants enjoy watching the night sky (and the day sky too, for sunspots, eclipses, etc.), and the plethora of objects found in it, mainly with portable telescopes and binoculars. Even though scientific research is not their main goal, many amateur astronomers make a contribution to astronomy by monitoring variable stars, tracking asteroids and discovering transient objects, such as comets.

Amateur astronomers watch the night sky during the Perseid meteor shower

Overview

The typical amateur astronomer is one who does not depend on the field of astronomy as a primary source of income or support, and does not have a professional degree or advanced academic training in the subject. Many amateurs are beginners or hobbyists, while others have a high degree of experience in astronomy and often assist and work alongside professional astronomers.

Amateur astronomy is usually associated with viewing the night sky when most celestial objects and events are visible, but sometimes amateur astronomers also operate during the day for events such as sunspots and solar eclipses. Amateur astronomers often look at the sky using nothing more than their eyes, but common tools for amateur astronomy include portable telescopes and binoculars.

People have studied the sky throughout history in an amateur framework, without any formal method of funding. It is only within about the past century, however, that amateur astronomy has become an activity clearly distinguished from professional astronomy, and other related activities.

Amateur astronomy objectives

Collectively, amateur astronomers observe a variety of celestial objects and phenomena. Common targets of amateur astronomers include the Moon, planets, stars, comets, meteor showers, and a variety of deep sky objects such as star clusters, galaxies, and nebulae. Many amateurs like to specialise in observing particular objects, types of objects, or types of events which interest them. One branch of amateur astronomy, amateur astrophotography, involves the taking of photos of the night sky. Astrophotography has become more popular for amateurs in recent times, as relatively sophisticated equipment, such as high quality CCD cameras, has become more affordable.

Most amateurs work at visible wavelengths, but a small minority experiment with wavelengths outside the visible spectrum. An early pioneer of radio astronomy was Grote Reber, an amateur astronomer who constructed the first purpose built radio telescope in the late 1930s to follow up on the discovery of radio wavelength emissions from space by Karl Jansky. Non-visual amateur astronomy includes the use of infrared filters on conventional telescopes, and also the use of radio telescopes. Some amateur astronomers use home-made radio telescopes, while others use radio telescopes that were originally built for astronomy research but have since been made available for use by amateurs. The One-Mile Telescope is one such example.

Common tools

Amateur astronomers use a range of instruments to study the sky, depending on a combination of their interests and resources. Methods include simply looking at the night sky with the naked eye, using binoculars, and using a variety of optical telescopes of varying power and quality, as well as additional sophisticated equipment, such as cameras, to study light from the sky in both the visual and non-visual parts of the spectrum. Commercial telescopes are available new and used, but in some places it is also common for amateur astronomers to build (or commission the building of) their own custom telescope. Some people even focus on amateur telescope making as their primary interest within the hobby of amateur astronomy.

Although specialized and experienced amateur astronomers tend to acquire more specialized and more powerful equipment over time, relatively simple equipment is often preferred for certain tasks. Binoculars, for instance, although generally of lower power than the majority of telescopes, also tend to provide a wider field of view, which is preferable for looking at some objects in the night sky.

Amateur astronomers also use star charts that, depending on experience and intentions, may range from simple planispheres through to detailed charts of very specific areas of the night sky. A range of astronomy software is available and used by amateur astronomers, including software that generates maps of the sky, software to assist with astrophotography, observation scheduling software, and software to perform various calculations pertaining to astronomical phenomena.

Amateur astronomers often like to keep records of their observations, which usually takes the form of an observing log. Observing logs typically record details about which objects were observed and when, as well as describing the details that were seen. Sketching is sometimes used within logs, and photographic records of observations have also been used in recent times.

The Internet is an essential tool of amateur astronomers. Almost all astronomy clubs, even those with very few members, have a web site. The popularity of CCD imaging among amateurs has led to large numbers of web sites being written by individuals about their images and equipment. Much of the social interaction of amateur astronomy occurs on mailing lists or discussion groups. Discussion group servers host numerous astronomy lists. A great deal of the commerce of amateur astronomy, the buying and selling of equipment, occurs online. Many amateurs use online tools to plan their nightly observing sessions using tools such as the Clear Sky Chart.

Common techniques

While a number of interesting celestial objects are readily identified by the naked eye, sometimes with the aid of a star chart, many others are so faint or inconspicuous that technical means are necessary to locate them. Many methods are used in amateur astronomy, but most are variations of a few specific techniques.

Star hopping

Star hopping is a method often used by amateur astronomers with low-tech equipment such as binoculars or a manually driven telescope. It involves the use of maps (or memory) to locate known landmark stars, and "hopping" between them, often with the aid of a finderscope. Because of its simplicity, star hopping is a very common method for finding objects that are close to naked-eye stars.

More advanced methods of locating objects in the sky include telescope mounts with *setting circles*, which assist with pointing telescopes to positions in the sky that are known to contain objects of interest, and *GOTO telescopes*, which are fully automated telescopes that are capable of locating objects on demand (having first been calibrated).

Setting circles

Setting circles are angular measurement scales that can be placed on the two main rotation axes of some telescopes. Since the widespread adoption of digital setting circles, any classical engraved setting circle is now specifically identified as an "analog setting circle" (ASC). By knowing the coordinates of an object (usually given in equatorial coordinates), the telescope user can use the setting circle to align the telescope in the appropriate direction before looking through its eyepiece. A computerized setting circle is called a "digital setting circle" (DSC). Although digital setting circles can be used to display a telescope's RA and Dec coordinates, they are not simply a digital read-out of what can be seen on the telescope's analog setting circles. As with go-to telescopes, digital setting circle computers (commercial names include Argo Navis, Sky Commander, and NGC Max) contain databases of tens of thousands of celestial objects and projections of planet positions.

To find an object, such as globular cluster NGC 6712, one does not need to look up the RA and Dec coordinates in a book, and then move the telescope to those numerical readings. Rather, the object is chosen from the database and arrow markers appear in the display which indicate the direction to move the telescope. The telescope is moved until the distance value reaches zero. When both the RA and Dec axes are thus "zeroed out", the object should be in the eyepiece. The user therefore does not have to go back and forth from some other database (such as a book or laptop) to match the desired object's listed coordinates to the coordinates on the telescope. However, many DSCs, and also go-to systems, can work in conjunction with laptop sky programs.

Computerized systems provide the further advantage of computing coordinate precession. Traditional printed sources are subtitled by the *epoch* year, which refers to the positions of celestial objects at a given time to the nearest year (e.g., J2005, J2007). Most such printed sources have been updated for intervals of only about every fifty years (e.g., J1900, J1950, J2000). Computerized sources, on the other hand, are able to calculate the right ascension and declination of the "epoch of date" to the exact instant of observation.

GoTo telescopes

GOTO telescopes have become more popular since the 1980s as technology has improved and prices have been reduced. With these computer-driven telescopes, the user typically enters the name of the item of interest and the mechanics of the telescope point the telescope towards that item automatically. They have several notable advantages for amateur astronomers intent on research. For example, GOTO telescopes tend to be faster for locating items of interest than star hopping, allowing more time for studying of the object. GOTO also allows manufacturers to add equatorial tracking to mechanically simpler alt-azimuth telescope mounts, allowing them to produce an over all less expensive product.

Remote Control telescopes

With the development of fast Internet in the last part of the 20th century along with advances in computer controlled telescope mounts and CCD cameras 'Remote Telescope' astronomy is now a viable means for amateur astronomers not aligned with major telescope facilities to partake in research and deep sky imaging. This enables anyone to control a telescope a large distance away in a dark location. The observers can image through the telescopes using CCD cameras. The digital data collected by the telescope is then transmitted and displayed to the user by means of the Internet. An example of a digital remote telescope operation for public use via the Internet is the The Bareket Observatory.

Imaging techniques

Amateur astronomers engage in many imaging techniques including film and CCD astrophotography. Because CCD imagers are linear, image processing may be used to subtract away the effects of light pollution, which has increased the popularity of astrophotography in urban areas.

Scientific research

Scientific research is most often not the *main* goal for many amateur astronomers, unlike professional astronomy. Work of scientific merit is possible, however, and many amateurs successfully contribute to the knowledge base of professional astronomers. Astronomy is sometimes promoted as one of the few remaining sciences for which amateurs can still contribute useful data. To recognize this, the Astronomical Society of the Pacific annually gives Amateur Achievement Awards for significant contributions to astronomy by amateurs.

The majority of scientific contributions by amateur astronomers are in the area of data collection. In particular, this applies where large numbers of amateur astronomers with small telescopes are more effective than the relatively small number of large telescopes that are available to professional astronomers. Several organizations, such as the Center for Backyard Astrophysics [1], exist to help coordinate these contributions.

Amateur astronomers often contribute toward activities such as monitoring the changes in brightness of variable stars and supernovae, helping to track asteroids, and observing occultations to determine both the shape of asteroids and the shape of the terrain on the apparent edge of the Moon as seen from Earth. With more advanced equipment, but still cheap in comparison to professional setups, amateur astronomers can measure the light spectrum emitted from astronomical objects, which can yield high-quality scientific data if the measurements are performed with due care. A relatively recent role for amateur astronomers is searching for overlooked phenomena (e.g., Kreutz Sungrazers) in the vast libraries of digital images and other data captured by Earth and space based observatories, much of which is available over the Internet.

In the past and present, amateur astronomers have played a major role in discovering new comets. Recently however, funding of projects such as the Lincoln Near-Earth Asteroid Research and Near Earth Asteroid Tracking projects has meant that *most* comets are now discovered by automated systems, long before it is possible for amateurs to see them.

Societies

There are a large number of amateur astronomical societies around the world that serve as a meeting point for those interested in amateur astronomy, whether they be people who are actively interested in observing or "armchair astronomers" who may simply be interested in the topic. Societies range widely in their goals, depending on a variety of factors such as geographic spread, local circumstances, size, and membership. For instance, a local society in the middle of a large city may have regular meetings with speakers, focusing less on observing the night sky if the membership is less able to observe due to factors such as light pollution.

It is common for local societies to hold regular meetings, which may include activities such as star parties or presentations. Societies are also a meeting point for people with particular interests, such as amateur telescope making.

Notable amateur astronomers

- George Alcock, discoverer of comets and novae.
- Thomas Bopp, shared the discovery of Comet Hale-Bopp in 1995 with unemployed PhD physicist Alan Hale.
- Robert Burnham, Jr., author of the *Celestial Handbook*.
- Andrew Ainslie Common (1841–1903), built his own very large reflecting telescopes and demonstrated that photography could record astronomical features invisible to the human eye.
- Robert E. Cox (1917–1989) who conducted the "Gleanings for ATMs" column in *Sky and Telescope* magazine for 21 years.
- John Dobson (1915), whose name is associated with the Dobsonian telescope, a simplified design for Newtonian reflecting telescopes.
- Robert Owen Evans is a minister of the Uniting Church in Australia and an amateur astronomer who holds the all-time record for visual discoveries of supernovae.
- Clinton B. Ford (1913–1992), who specialized in the observation of variable stars.
- Will Hay, the famous comedian and actor, who discovered a white spot on Saturn.
- Walter Scott Houston (1912–1993) who wrote the "Deep-Sky Wonders" column in *Sky & Telescope* magazine for almost 50 years.
- Albert G. Ingalls (1888–1958), editor of *Amateur Telescope Making, Vols. 1-3* and "The Amateur Scientist". He and Russell Porter are generally credited with having initiated the amateur telescope making movement in the U. S.
- David H. Levy discovered or co-discovered 22 comets including Comet Shoemaker-Levy 9, the most for any individual.
- Sir Patrick Moore, presenter of the BBC's long-running *The Sky at Night* and author of many books on astronomy.
- Leslie Peltier was a prolific discoverer of comets and well-known observer of variable stars.
- John M. Pierce (1886–1958) was one of the founders of the Springfield Telescope Makers. In the 1930s he published a series of 14 articles on telescope making in Hugo Gernsback's "Everyday Science and Mechanics" called "Hobbygraphs".
- Tim Puckett, the principal investigator of the Puckett Observatory World Supernova Search team, which has discovered over 200 supernovae since 1998
- Russell W. Porter founded Stellafane and has been referred to as the "founder"[2] [3] or one of the "founders" of amateur telescope making."[4]
- Isaac Roberts, early experimenter in astronomical photography.
- Grote Reber (1911—2002), pioneer of radio astronomy constructing the first purpose built radio telescope and conducted the first sky survey in the radio frequency.

Prizes recognizing amateur astronomers

- Amateur Achievement Award of Astronomical Society of the Pacific
- Astronomical League Award [5]
- Blair Medal of the Western Amateur Astronomers [6]
- Chambliss Amateur Achievement Award

References

[1] http://cbastro.org

[2] **Mirror Mirror** By Mark Pendergrast, Page 236 (http://books.google.com/books?id=XCbTj74cgc4C&pg=PA236&dq=father+of+amateur+telescope+making&lr=&ei=j-JDSayNNYbWlQTTkJnjDg)

[3] The Springfield Stars Club - Stars Club History - *"Russell Porter, considered to be the founder of amateur telescope making."* (http://www.reflector.org/history.php)

[4] Albert G. Ingalls is sometime given credit as co-founder of this movement, **BORDER TRADING: THE AMATEUR-PROFESSIONAL PARTNERSHIP IN VARIABLE STAR ASTRONOMY** by Sheila Kannappan, Page 7 (http://www.physics.unc.edu/~sheila/entirethesis.pdf)
[5] Astronomical League Award Winners (http://www.astroleague.org/al/awards/alaward/alawdprv.html)
[6] G. Bruce Blair Award Medal Recipients (http://www.waa.av.org/Blair_recip_99.html)

Further reading

- *Seeing in the Dark: How Backyard Stargazers Are Probing Deep Space and Guarding Earth from Interplanetary Peril*, by Timothy Ferris, ISBN 0-684-86579-3
- *The Complete Manual Of Amateur Astronomy*, by P. Clay Sherrod

External links

- Amateur Astronomy Magazine (http://www.amateurastronomy.com/)

The International Year of Astronomy 2009

International Year of Astronomy

The IYA2009 logo.

The **International Year of Astronomy** (**IYA2009**) was a year-long celebration of astronomy that took place in 2009 to coincide with the 400th anniversary of the first recorded astronomical observations with a telescope by Galileo Galilei and the publication of Johannes Kepler's *Astronomia nova* in the 17th century.[1] The Year was declared by the 62nd General Assembly of the United Nations.[2] [3] A global scheme, laid out by the International Astronomical Union (IAU), was also endorsed by UNESCO, the UN body responsible for educational, scientific, and cultural matters.[4]

The IAU coordinated the International Year of Astronomy in 2009. This initiative was an opportunity for the citizens of Earth to gain a deeper insight into astronomy's role in enriching all human cultures. Moreover, served as a platform for informing the public about the latest astronomical discoveries while emphasizing the essential role of astronomy in science education. IYA2009 was sponsored by Celestron and Thales Alenia Space.

Significance of 1609

International Year of Astronomy commemorative coin.

In 1609, Galileo Galilei first turned one of his telescopes to the night sky and made astounding discoveries that changed mankind's conception of the world forever: mountains and craters on the Moon, a plethora of stars invisible to the naked eye, and moons around Jupiter.[5] Astronomical observatories around the world promised to reveal how planets and stars are formed, how galaxies assemble and evolve, and what the structure and shape of our Universe actually are. In the same year, Johannes Kepler published his work *Astronomia nova*, in which he described the fundamental laws of planetary motions.

On 25 September 1608, Hans Lippershey, a young man from Middleburg, travelled to the Hague, the then capital of the Netherlands, to demonstrate one of his inventions to the Dutch government: the telescope. Although Hans was not awarded the patent, Galileo heard of this story and decided to use the "Dutch perspective glass" and point it towards the heavens.

Intended purpose

Vision

The vision of IYA2009 was to help people rediscover their place in the Universe through the sky, and thereby engage a personal sense of wonder and discovery. IYA2009 activities took place locally, nationally, regionally and internationally. National Nodes were formed in each country to prepare activities for 2009. These nodes established collaborations between professional and amateur astronomers, science centres and science communicators. More than 100 countries were involved, and well over 140 participated eventually. To help coordinate this huge global programme and to provide an important resource for the participating countries, the IAU established a central Secretariat and the IYA2009 website as the principal IYA2009 resource for public, professionals and media alike.[6]

Aims

Astronomy, the oldest science in history, has played an important role in most, if not all, cultures over the ages. The International Year of Astronomy 2009 (IYA2009) is intended to be a global celebration of astronomy and its contributions to society and culture, stimulating worldwide interest not only in astronomy, but in science in general, with a particular slant towards young people.

The IYA2009 marks the monumental leap forward that followed Galileo's first use of the telescope for astronomical observations, and portrays astronomy as a peaceful global scientific endeavour that unites amateur and professional astronomers in an international and multicultural family that works together to find answers to some of the most fundamental questions that humankind has ever asked. The aim of the Year is to stimulate worldwide interest in astronomy and science under the central theme "The Universe, Yours to Discover."

Several committees were formed to oversee the vast majority of IYA2009 activities ("sidewalk astronomy" events in planetariums and public observatories), which spun local, regional and national levels. These committees are collaborations between professional and amateur astronomers, science centres and science communicators. Individual countries will be undertaking their own initiatives as well as assessing their own national needs, while the IAU acted as the event's coordinator and catalyst on a global scale. The IAU plans to liaise with, and involve, as many as possible of the ongoing outreach and education efforts throughout the world, including those organized by amateur astronomers.

Goals

The major goals of IYA2009 were to:

1. Increase scientific awareness;
2. Promote widespread access to new knowledge and observing experiences;
3. Empower astronomical communities in developing countries;
4. Support and improve formal and informal science education;
5. Provide a modern image of science and scientists;
6. Facilitate new networks and strengthen existing ones;
7. Improve the gender-balanced representation of scientists at all levels and promote greater involvement by underrepresented minorities in scientific and engineering careers;
8. Facilitate the preservation and protection of the world's cultural and natural heritage of dark skies in places such as urban oases, national parks and astronomical sites.

As part of the scheme, IYA2009 helped less well-established organizations from the developing world to become involved with larger organizations and deliver their contributions, linked via a huge global network. This initiative also aims at reaching economically disadvantaged children across the globe and enhance their understanding of the world.[7]

The Secretariat

The central hub of the IAU activities for the IYA2009 was the United Nations Secretariat. This was established to coordinate activities during the planning, execution and evaluation of the Year. The Secretariat is based in the European Southern Observatory headquarters in the town of Garching near Munich, Germany. The Secretariat will liaise continuously with the National Nodes, Task Groups, Partners and Organizational Associates, the media and the general public to ensure the progress of the IYA2009 at all levels. The Secretariat and the website are the most important coordination and resource centers for all the participating countries, but most particularly for those developing countries that lack the national resources to mount major events alone.

Cornerstone projects

The International Year of Astronomy 2009 was supported by eleven Cornerstone projects. These are global programs of activities centered on specific themes and are some of the projects that helped to achieve IYA2009's main goals; whether it is the support and promotion of women in astronomy, the preservation of dark-sky sites around the world or educating and explaining the workings of the Universe to millions, the eleven Cornerstones were the key elements in the success of IYA2009.

100 Hours of Astronomy

100 Hours of Astronomy (**100HA**)[8] is a worldwide astronomy event that ran April 2nd-5th, 2009 and was part of the scheduled global activities of the International Year of Astronomy 2009. The main goals of 100HA was to have as many people throughout the world as possible looking through a telescope just as Galileo did for the first time 400 years ago. Event included special webcasts, students and teachers activities, a schedule of events at science centers, planetariums and science museums as well as 24 hours of sidewalk astronomy, which allowed the opportunity for public observing sessions to as many people as possible.

Galileoscope

The **Galileoscope**[9] is a worldwide astronomy event that ran April 2nd-5th, program is to share a personal experience of practical astronomical observations with as many people as possible across the world. It is collaborating with the US IYA2009 National Node to develop a simple, accessible, easy-to-assemble and easy-to-use telescope that can be distributed by the millions. In theory, every participant in an IYA2009 event should be able to take home one of these little telescopes, enabling them to observe with an instrument similar to Galileo's one.

Cosmic Diary

The **Cosmic Diary**[10] is a worldwide astronomy event that ran April 2nd-5th, is not about the science of astronomy, but about what it is like to be an astronomer. Professionals will blog in texts and images about their life, families, friends, hobbies and interests, as well as their work, latest research findings and the challenges they face. The bloggers represent a vibrant cross-section of working astronomers from all around the world. They write in many different languages and come from five continents. They have also written feature article "explanations" about their specialist fields, which are highlighted in? the website. NASA, ESA and ESO all have sub-blogs as part of the Cosmic Diary Cornerstone.

The Portal to the Universe

The Portal to the Universe (**PTTU**)[11] is a worldwide astronomy event that ran April 2–5, provides a global, one-stop portal for online astronomy contents, serving as an index, aggregator and a social networking site for astronomy content providers, laypeople, press, educators, decision-makers and scientists. PTTU will feature news, image, event and video aggregation; a comprehensive directory of observatories, facilities, astronomical societies, amateur astronomy societies, space artists, science communication universities; and Web 2.0 collaborative tools, such as the ranking of different services according to popularity, to promote interaction within the astronomy multimedia community. In addition, a range of "widgets" (small applications) will be developed to tap into existing "live data". Modern technology and the standardisation of metadata make it possible to tie all the suppliers of such information together with a single, semi-automatically updating portal.

She Is an Astronomer

Promoting gender equality and empowering women is one of the United Nations Millennium Development Goals. **She Is an Astronomer**[12] is a worldwide astronomy event that ran April 2^{nd}-5^{th}, project will promote gender equality in astronomy (and science in general), tackling bias issues by providing a web platform where information and links about gender balance and related resources are collected. The aim of the project is to provide neutral, informative and accessible informations to female professional and amateur astronomers, students, and those who are interested in the gender equality problem in science. We believe that providing this information will help increasing the interest of young girls in studying and pursuing a career in astronomy. Another objective of the project is to build and maintain an internet based, easy-to-handle forum and database, where people regardless of geographical location can read about the subject, ask questions and find answers. There will also be the option to discuss astronomy sector specific problems, such as observing times and family duties.

Dark Skies Awareness

Dark Skies Awareness[13] is a worldwide astronomy event that ran from April 2 to 5. The IAU collaborated with the U.S. National Optical Astronomy Observatory (NOAO), representatives of the International Dark-Sky Association (IDA), the Starlight Initiative, and other national and international partners in dark sky and environmental education on several related themes. The focus will be on three main citizen-scientist programs to measure local levels of light pollution. These programs will take the form of "star hunts" or "star counts", providing people with a fun and direct way to acquire heightened awareness about light pollution through firsthand observations of the night sky. Together the three programs will cover the entire International Year of Astronomy 2009, namely GLOBE at Night (in March), the Great World Wide Star Count (in October) and How Many Stars (January, February, April through September, November and December).

UNESCO and the IAU are working together to implement a research and education collaboration as part of UNESCO's thematic initiative, **Astronomy and World Heritage**[14] is a worldwide astronomy event that ran April 2^{nd}-5^{th}, . The main objective is to establish a link between science and culture on the basis of research aimed at acknowledging the cultural and scientific values of properties connected with astronomy. This programme provides an opportunity to identify properties related to astronomy located around the world, to preserve their memory and save them from progressive deterioration. Support from the international community is needed to implement this activity and to promote the recognition of astronomical knowledge through the nomination of sites that celebrate important achievements in science.

Galileo Teacher Training Program

The **Galileo Teacher Training Program** (**GTTP**): the International Year of Astronomy 2009 provides an excellent opportunity to engage the formal education community in the excitement of astronomical discovery as a vehicle for improving the teaching of science in classrooms around the world. To help training teachers in effective astronomy communication and to sustain the legacy of IYA2009, the IAU — in collaboration with the National Nodes and leaders in the field such as the Global Hands-On Universe project, the US National Optical Astronomy Observatory and the Astronomical Society of the Pacific — is embarking on a unique global effort to empower teachers by developing the **Galileo Teacher Training Program** (GTTP).[15]

The GTTP goal is to create a worldwide network of certified "Galileo Ambassadors" by 2012. These Ambassadors will train "Galileo Master Teachers" in the effective use and transfer of astronomy education tools and resources into classroom science curricula. The Galileo Teachers will be equipped to train other teachers in these methodologies, leveraging the work begun during IYA2009 in classrooms everywhere. Through workshops, online training tools and basic education kits, the products and techniques developed by this program can be adapted to reach locations with few resources of their own, as well as computer-connected areas that can take advantage of access to robotic optical and radio telescopes, webcams, astronomy exercises, cross-disciplinary resources, image processing and digital universes (web and desktop planetariums). Among GTTP partners, the Global Hands-On Universe project is a leader.

Universe Awareness

Universe Awareness (**UNAWE**)[16] is a worldwide astronomy event that ran April 2nd-5th, is an international program that exposes very young children in under-privileged environments to the scale and beauty of the Universe. Universe Awareness illustrates the multicultural origins of modern astronomy in an effort to broaden children's minds, awaken their curiosity in science and stimulate global citizenship and tolerance. Using the sky and children's natural fascination with it as common ground, UNAWE creates an international awareness of our place in the Universe and our place on Earth.

From Earth to the Universe

The Cornerstone project **From Earth to the Universe** (**FETTU**)[17] is a worldwide public science event that began in June 2008 and is still ongoing through 2011. This project endeavors to bring astronomy images and their science to a wider audience in non-traditional informal learning venues. In placing these astronomy exhibitions in public parks, metro stations, art centers, hospitals, shopping malls and other accessible locations, it is hoped that individuals who might normally ignore or even dislike astronomy, or science in general, will be engaged.

Developing Astronomy Globally

The **Developing Astronomy Globally**[18] is a worldwide astronomy event that ran April 2nd-5th, Cornerstone project acknowledges that astronomy needs to be developed in three key areas: professionally (universities and research); publicly (communication, media, and amateur groups) and educationally (schools and informal education structures). The focus will be on regions that do not already have strong astronomical communities. The implementation will be centred on training, development and networking in each of these three key areas. This Cornerstone will use the momentum of IYA2009 to help establish and enhance regional structures and networks that work on the development of astronomy around the world. These networks will support the current and future development work of the IAU and other programmes and should ensure that developing regions can benefit from IYA2009 and the work of the other Cornerstone projects. It should also address the question of the contribution of astronomy to development.

Galilean Nights

The **Galilean Nights**[19] is a worldwide astronomy event that ran April 2nd-5th, project involves both amateur and professional astronomers around the globe taking to the streets their telescopes and pointing them as Galileo did 400 years ago. The sources of interest will be Jupiter and its moons, the Sun, our Moon and many others celestial maravels. The event is scheduled to take place on 22–24 October 2009. Astronomers will share their knowledge and enthusiasm for space by encouraging as many people as possible to look through a telescope at our planetary neighbours.

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External links

- Official website (http://http://www.astronomy2009.org) of IYA2009 (includes all events and projects)
- Official website (http://http://www.iau.org/iau0606_IYA.408.0.html) of the International Astronomical Union (IAU)
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