HISTORY OF ASTRONOMY

Largely on the basis of Greek astronomy, the sky is divided somewhat arbitrarily into sections called constellations. Greek mythological characters dominate the original names, which were given to conspicuous arrangements of stars that roughly outline the fanciful figure named. For example, when looking at a particular apparent group of stars visible in the evening sky during the spring, the Greeks imagined the figure of a lion and named the grouping Leo. Of the 88 currently recognized constellations, 48 have come from the listing of the ancient astronomer PTOLEMY. The remainder were added by subsequent astronomers to fill in the areas omitted by the Greeks, especially those in the southern part of the celestial sphere.

Constellations generally do not involve physically related groups of stars, but are merely apparent patterns in the sky made by stars at vastly different true distances from the Earth. In modern astronomy constellations are a convenient method of describing different directions in the sky. The sky is completely divided into constellations, and their borders are similar to the political borders of states or counties rather than to physical boundaries of any significance.

The constellations may be divided into three groups: (1) the equatorial constellations that lie on either side of the celestial equator, which is the projection onto the sky of the Earth's equator; (2) the north circumpolar constellations, which never set for observers at northern mid-latitudes; and (3) the south circumpolar constellations, which also are always present in the sky from southern terrestrial latitudes. The ZODIAC, widely used in ASTROLOGY, consists of 12 constellations through which the Sun appears to move because of the Earth's yearly orbital motion.

Ursa Major, part of which is commonly called the BIG DIPPER or THE PLOUGH, is a well-known northern constellation; for most of North America and Europe it is circumpolar. Named the "big bear" by the Greeks, it is a handy nighttime measure of season and time because it is high in the sky on summer evenings and low near the northern horizon on winter evenings. The two stars forming the lip of the Big Dipper point to the pole star, POLARIS, which lies at the end of the Little Dipper's handle. The LITTLE DIPPER, in turn, is the end of the tail of the Greeks' "little bear," or Ursa Minor.

A conspicuous star grouping in the sky is the large equatorial constellation ORION, named by the Greeks for the great hunter. Consisting primarily of a near rectangle of bright stars, Orion is visible during the Northern Hemisphere's winter and the Southern Hemisphere's summer. Three bright stars in the middle outline Orion's belt, and three fainter stars (the middle one actually a nebula) delineate his sword.
Opposite Orion is another well-known constellation visible in the summer sky from northern latitudes--CYGNUS, the swan, also known as the Northern Cross, which lies across a bright part of the Milky Way

The history of astronomy comprises three broadly defined areas that have characterized the science of the heavens since its beginnings. With varying degrees of emphasis among particular civilizations and during particular historical periods, astronomers have sought to understand the motions of celestial bodies, to determine their physical characteristics, and to study the size and structure of the universe. The latter study is known as COSMOLOGY.

MOTIONS OF SUN, MOON, AND PLANETS

From the dawn of civilization until the time of Copernicus, astronomy was dominated by the study of the motions of celestial bodies. Such work was essential for ASTROLOGY, for the determination of the CALENDAR, and for the prediction of ECLIPSES, and it was also fueled by the desire to reduce irregularity to order and to predict positions of celestial bodies with ever-increasing accuracy. The connection between the calendar and the motions of the celestial bodies is especially important, because it meant that astronomy was essential to determining the times for the most basic functions of early societies, including the planting and harvesting of crops and the celebration of religious feasts.

The celestial phenomena observed by the ancients were the same as those of today. The Sun progressed steadily westward in the course of a day, and the stars and the five visible planets did the same at night. The Sun could be observed at sunset to have moved eastward about one degree a day against the background of the stars, until in the course of a year it had completely traversed the 360 degree path of constellations that came to be known as the ZODIAC. The planets generally also moved eastward along the zodiac, with 8 degrees of the Sun's apparent annual path (the ecliptic), but at times they made puzzling reversals in the sky before resuming their normal eastward motion. By comparison, the Moon moved across the ecliptic in about 27 1/3 days and went through several phases. The earliest civilizations did not realize that these phenomena were in part a product of the motion of the Earth itself; they merely wanted to predict the apparent motions of the celestial bodies.

Although the Egyptians must have been familiar with these general phenomena, their systematic study of celestial motions was limited to the connection of the flooding of the Nile with the first visible rising of the star Sirius. An early attempt to develop a calendar based on the Moon's phases was abandoned at too complex, and as a result astronomy played a lesser role in Egyptian civilization than it otherwise might have. Similarly, the Chinese did not systematically attempt to determine celestial motions. Surprising evidence of a more substantial interest in astronomy is found the presence of ancient STONE ALIGNMENTS and STONE CIRCLES found throughout Europe and Great Britain, the most notable of which is STONEHENGE in England. As early as 3000 BC, the collection of

massive stones at Stonehenge functioned as an ancient observatory, where priests followed the annual motion of the Sun each morning along the horizon in order to determine the beginning of the seasons. By about 2500 BC, Stonehenge may have been used to predict eclipses of the Moon. Not until 1000 AD were similar activities undertaken by New World cultures.

Astronomy reached its first great heights among the Babylonians. In the period from about 1800 to 400 BC, the

  Babylonians developed a calendar based on the motion of the Sun and the phases of the Moon. During the 400 years that followed, they focused their attention on the prediction of the precise time the new crescent Moon first became visible and defined the beginning of the month according to this event. Cuneiform tablets deciphered only within the last century demonstrate that the Babylonians solved the problem within an accuracy of a few minutes of time; this was achieved by compiling precise observational tables that revealed smaller variations in the velocity of the Sun and of the Moon than ever before measured. These variations--and others such as changes in the Moon's latitude--were analyzed numerically by noting how the variations fluctuated with time in a regular way. They used the same numerical method, utilizing the same variations, to predict lunar and solar eclipses.

  The Greeks used a geometrical rather than a numerical approach to understand the same celestial motions. Influenced by Plato's metaphysical concept of the perfection of circular motion, the Greeks sought to represent the motion of the divine celestial bodies by using spheres and circles. This explanatory method was not upset until KEPLER replaced the circle with the ellipse in 1609.

  Plato's student EUDOXUS OF CNIDUS, c.408-c.355 BC, was the first to offer a solution along these lines. He assumed that each planet is attached to one of a group of connected concentric spheres centered on the Earth, and that each planet rotates on differently oriented axes to produce the observed motion. With this scheme of crystalline spheres he failed to account for the variation in brightness of the planets; the scheme was incorporated, however, into ARISTOTLE's cosmology during the 4th century BC. Thus the Hellenic civilization that culminated with Aristotle attempted to describe a physical cosmology. In contrast, the Hellenistic civilization that followed the conquests of Alexander the Great developed over the next four centuries soon predominant mathematical mechanisms to explain celestial phenomena. The basis for this approach was a variety of circles known as eccentrics, deferents, and epicycles. The Hellenistic mathematician APOLLONIUS OF PERGA, c.262-c.190 BC, noted that the annual motion of the Sun can be approximated by a circle with the Earth slightly off-center, or eccentric, thus accounting for the observed variation in speed over a year. Similarly, the Moon traces an eccentric circle in a period of 27 1/3 days. The periodic reverse, or retrograde,

motion of the planets across the sky required a new theoretical device. Each planet was assumed to move with uniform velocity around a small circle (the epicycle) that moved around a larger circle (the deferent), with a uniform velocity appropriate for each particular planet. HIPPARCHUS, c.190-120 BC, the most outstanding astronomer of ancient times, made refinements to the theory of the Sun and Moon based on observations from Nicaea and the island of Rhodes, and he gave solar theory essentially its final form. It was left for PTOLEMY, c.100-c.165, to compile all the knowledge of Greek astronomy in the Almagest and to develop the final lunar and planetary theories.

  With Ptolemy the immense power and versatility of these combinations of circles as explanatory mechanisms reached new heights. In the case of the Moon, Ptolemy not only accounted for the chief irregularity, called the equation of the center, which allowed for the prediction of eclipses. He also discovered and corrected another irregularity, evection, at other points of the Moon's orbit by using an epicycle on a movable eccentric deferent, whose center revolved around the Earth. When Ptolemy made a further refinement known as prosneusis, he was able to predict the place of the Moon within 10', or 1/6 deg, of arc in the sky; these predictions were in good agreement with the accuracy of observations made with the instruments used at that time. Similarly, Ptolemy described the motion of each planet in the Almagest, which passed, with a few notable elaborations, through Islamic civilization and on to the Renaissance European civilization that nurtured COPERNICUS.

  The revolution associated with the name of Copernicus was not a revolution in the technical astronomy of explaining motions, but rather belongs to the realm of cosmology. Prodded especially by an intense dislike of one of Ptolemy's explanatory devices, known as the equant, which compromised the principle of uniform circular motions, Copernicus placed not the Earth but the Sun at the center of the universe; this view was put forth in his De revolutionibus orbium caelestium (On the Revolutions of the Heavenly Spheres, 1543). In that work, however, he merely adapted the Greek system of epicycles and eccentrics to the new arrangement. The result was an initial simplification and harmony as the diurnal and annual motions of the Earth assumed their true meaning, but no overall simplification in the numbers of epicycles needed to achieve the same accuracy of prediction as had Ptolemy. It was therefore not at all clear that this new cosmological system held the key to the true mathematical system that could accurately explain planetary motions.

  The German astronomer Johannes KEPLER provided a daring solution to the problem of planetary motions and demonstrated the validity of the heliocentric theory of Copernicus, directly associating the Sun with the physical cause of planetary motions. At issue for Kepler was a mere 8' discrepancy between theory and observation for the position of the planet Mars. This degree of accuracy would have delighted Ptolemy or Copernicus, but it was unacceptable in light of the observations of the Danish astronomer Tycho BRAHE,

made from Uraniborg Observatory with a variety of newly constructed sextants and quadrants and accurate to within 1' to 4'. This new scale of accuracy revolutionized astronomy, for in his Astronomia nova (New Astronomy, 1609), Kepler announced that Mars and the other planets must move in elliptical orbits, readily predictable by the laws of planetary motion that he proceeded to expound in this work and in the Harmonices mundi (Harmonies of the World, 1619). Only by abandoning the circle could the heavens be reduced to an order comparable to the most accurate observations.

   Kepler's laws and the Copernican theory reached their ultimate verification with NEWTON's enunciation of the laws of universal gravitation in the Principia (1687). In these laws, the Sun was assigned as the physical cause of planetary motion. The laws also served as the theoretical basis for deriving Kepler's laws. During the 18th century, the implications of gravitational astronomy were recognized and analyzed by able mathematicians, notably Jean d'ALEMBERT, Alexis CLAIRAUT, Leonhard EULER, Joseph LAGRANGE, and Pierre LAPLACE. The science of CELESTIAL MECHANICS was born and the goal of accurate prediction was finally realized.

   During all of this discussion the stars had been regarded as fixed. While working on his catalog of 850 stars, however, Hipparchus had already recognized the phenomenon known as the PRECESSION OF THE EQUINOXES, an apparent slight change in the positions of stars over a period of hundreds of years caused by a wobble in the Earth's motion. In the 18th century, Edmond HALLEY determined that the stars had their own motion, known as PROPER MOTION, that was detectable even over a period of a few years. The observations of stellar positions, made with transit instruments through the monumental labors of such scientists as John FLAMSTEED, laid the groundwork for solving a cosmological problem of another era: the distribution of the stars and the structure of the universe.

 PHYSICAL CHARACTERISTICS OF CELESTIAL BODIES

   The study of the motions of the celestial bodies required only that they be regarded as mere points of light. But already in the 4th century BC, Aristotle proposed in his De caelo (On the Heavens) a theory of the physical nature of these bodies, which conferred on them the properties of perfection and unchangeability thought appropriate to the divine celestial regions, in contrast to the ever-changing Earth. In the next century, ARISTARCHUS OF SAMOS, again exhibiting the mathematical penchant of the Hellenistic era, offered an observationally based estimate, although about ten times too low, of the sizes of the Sun and Moon. These size estimates were universally admired, and Aristotle's physical hypothesis only sporadically challenged, by medieval commentators.

Moon and Planets
   The physical similarity of the Earth and planets became a matter of significant inquiry

only after Copernicus showed that the Earth and all of the planets are in motion around the central Sun. The question might have remained forever unresolved had not GALILEO GALILEI constructed a telescope, although not the first in Europe, which he turned toward the heavens in 1609. The results, announced in the Sidereus nuncius (Sidereal Messenger, 1610), were shattering to the Aristotelian view. The Moon was found to be a mountainous body "not unlike the face of the Earth." Galileo's further discovery of the moons of Jupiter and the phases of Venus was more evidence that the planets had Earthlike characteristics.

  Such discoveries--extremely important as verification for the physical reality of the Copernican theory--slowly accumulated throughout the 17th and 18th centuries. The nature of the Moon was discussed in increasing detail in Kepler's Somnium (1634), Johannes HEVELIUS's Selenographia (1647), and G. B. RICCIOLI's Almagestum novum (1651). Christiaan HUYGENS, the greatest observational astronomer of the 17th century, first correctly interpreted the rings of Saturn in his Systema Saturnium (1659), observed dark markings on Mars, and belts of clouds on Jupiter, and speculated that Venus was shrouded in clouds. With more refined telescopes, such as those built by Sir William HERSCHEL in England, the details of the solar system became better known. Herschel himself made the spectacular discovery of the planet Uranus in 1781. In 1846, the presence of yet another planet (Neptune), predicted by J. C. ADAMS and U. J. J. LEVERRIER, was confirmed observationally--a triumph for both theory and observation. With the invention of SPECTROSCOPY in the 1860s, and with the work of Sir William Huggins and Norman Joseph LOCKYER in England, P. A. SECCHI in Rome, Cesar JANSSEN in Paris, Lewis Rutherfurd (1816-92) in the United States, and Hermann Vogel (1842-1907) in Germany, the science of astrophysics was born. By spreading the light of the celestial bodies into the constituent colors of the SPECTRUM, each interspersed with lines characteristic of the elements present, a powerful new tool was given to the astronomer. The ability to determine the chemical composition of planetary atmospheres and even of the stars, a task which the positivist philosopher Auguste Comte had offered less than 30 years before as the paradigm of what science could never achieve, now became possible.

Sun and Stars

  Astrophysics yielded its most substantial results in the study of the Sun and stars, where the myriads of observed spectral lines were gradually interpreted as a precise set of chemical fingerprints. With spectroscopy and the almost simultaneous invention of photography, astronomers compiled great catalogs mapping the solar spectrum. Knowledge of the Sun, which had not advanced substantially since Galileo's discovery of sunspots, now outstripped planetary astronomy. The means were at hand to determine the temperature, composition, age, and structure of the Sun and to compare this data with that of the other stars, which were now for the first time proved to be other suns.

In conjunction with advances in nuclear physics the investigations of the latter half of the 19th century led to the building of a firm foundation for a discussion in the first quarter of the 20th century of the internal constitution and evolution of stars. This program was pioneered by A. S. EDDINGTON and Karl SCHWARZSCHILD. By providing a wealth of data previously unavailable, astrophysics fueled the controversy over the possible existence of EXTRATERRESTRIAL LIFE not only in our solar system, but throughout a universe of other possible solar systems.

COSMOLOGY: THE STRUCTURE OF THE UNIVERSE

The study of the motions and physical characteristics of celestial bodies could be undertaken on a case-by-case basis. COSMOLOGY, on the other hand, by definition had to mold from the whole body of observations a coherent theory of the structure of the universe. From the time of Aristotle until the Copernican revolution this structure had been conceived firmly as Earth-centered, in spite of Aristarchus's heliocentric views. Between the inner Earth and the outer sphere of fixed stars each planet was considered imbedded in a crystalline sphere that was in uniform circular motion. Within this neat compact structure the whole history of humankind and the universe unfolded. The work of Kepler and Newton on planetary motion and of Galileo and others on the physical nature of the planets resulted in the gradual acceptance during the 17th century of the Copernican heliocentric hypothesis as a physically valid system. This acceptance had profound implications for cosmology. Not only did Kepler's theory of ellipses make obsolete the theory of crystalline spheres of Aristotle, the absence of any detectable stellar PARALLAX--apparent change in the direction of a star--even when measured from opposite sides of the Earth's orbit, demonstrated the necessity of acknowledging the enormous size of the universe. The subsequent shift from the closed tightly structured world to an infinite homogenous universe was one of the landmarks in the history of astronomy. Giordano BRUNO and Thomas DIGGES were among its earliest exponents, and DESCARTES and Newton incorporated it as a standard part of the new view of the universe.

The Galaxy

The downfall of the concept of the sphere of fixed stars opened the way for investigations into the distribution of the stars. The phenomenon of the Milky Way, shown by Galileo to consist of myriads of stars, hinted that some previously unsuspected structure might exist among the stars. In 1750 the English theologian and astronomer Thomas WRIGHT sought to explain the brilliantly luminous band of the Milky Way as a collection of stars that extended further in the direction of the band than in other directions. In 1780, William Herschel initiated an observational program of star counts, or gauges, of selected regions of the sky. By assuming that the brightness of a star is a

measure of its distance from the Earth, this program resulted in a picture of a flattened disc-shaped system with the Sun near the center. In spite of his incorrect assumptions, Herschel's research marked the beginnings of an understanding of the structure of the stellar system and earned him the title of founder of stellar astronomy.

Because of the lack of a direct method for determining stellar distances, progress in cosmology lagged for more than a century after Herschel's star gauges. Only with improved instrumentation did Friedrich BESSEL, Wilhelm STRUVE, and Thomas Henderson (1798-1844) in 1838 succeed in measuring the first stellar distances. An annual parallactic shift of .31" in the position of the star 61 Cygni implied a distance equivalent to 590,000 times that of the Earth from the Sun. But difficulties innate to the method resulted in fewer than 300 known stellar distances by the end of the century--far too few to solve the problem of the structure of the stellar system.

Along with continuous attempts at parallax measurements, a major task of 19th-century astronomers was the compilation of ASTRONOMICAL CATALOGS AND ATLASES containing the precise magnitudes, positions, and motions of stars. The work of Friedrich ARGELANDER, David GILL and J. C. KAPTEYN is especially notable in this regard, with the latter two astronomers utilizing new photographic techniques. Such surveys yielded the two-dimensional distribution of stars over the celestial sphere. Heroic efforts were made, especially by Hugo von Seeliger, to extrapolate from this data to an understanding of three-dimensional structure.

Real progress was finally made only through an analysis of the extremely small motions of stars, known as proper motion. Building on the astronomical catalogs of James BRADLEY, G. F. Arthur von Auwers (1838-1915), and Lewis Boss (1846-1912), and on his own observations, J. C. Kapteyn, exploiting the new field of statistical astronomy, applied statistical methods of distance determination to find an ellipsoidal shape for the system of stars. In 1904 he found that the stars streamed in two directions. Only in 1927 did J. H. OORT, working on the basis of Bertil LINDBLAD's studies, determine that Kapteyn's observational data could be accounted for if the galaxy were assumed to be rotating. In a cosmological shock comparable to the Copernican revolution four centuries before, the Galaxy was found to be 100,000 light years in diameter, with the Earth's solar system some 30,000 light years from the center.

Other Galaxies

The question of whether or not the Galaxy constituted the entirety of the universe came to a head in the 1920s with the debate between H. D. CURTIS and Harlow SHAPLEY. Curtis argued that nebulae are island universes similar to but separate from our own galaxy; Shapley included the nebulae in our galaxy. The controversy was settled when E. P. HUBBLE detected Cepheid stars in the Andromeda nebula and used them in a new method of distance determination, demonstrating that Andromeda and many other nebulae are far outside the Milky Way. Thus the universe was found to consist of a large

number of galaxies, spread like islands through infinite space. Such was the progress of astronomy from the time of the Babylonian observations of planetary motions to within a few degrees accuracy, to the Greek determinations of positions within a few minutes of arc, to the 19th-century measurements of parallax and proper motions in fractions of a second of arc. The concern of astronomers evolved from the determination of apparent motions to the observation of planetary surfaces, and ultimately to the measurement of the motions of the stars themselves, and of galaxies and systems of galaxies.