
*Several early astronomers, depicted in this 19th-century painting. From left: Tycho Brahe, Claudius Ptolemy, St. Augustine, Nicolaus Copernicus, Galileo Galilei (with pointer), and Andreas Cellarius, author of* Harmonia Macrocosmica. *At center is Urania, one of the nine Greek Muses.*

# Astronomy

Feb. 23, 1987: Ian Shelton, a Canadian astronomer working with a 10-inch telescope at the Las Campanas Observatory in northern Chile, notes a new bright object in the sky. That large spot of light, visible even without a telescope in a section of the Large Magellanic Cloud, roughly 163,000 light years from Earth, turns out to be a supernova—the first exploding star able to be seen by the naked eye since 1885.

Scientific observation of this recent celestial event, using the latest telescopes and astronomical instruments, has brought astronomy much public attention. Although most historians believe that astronomy is the oldest physical science, its great breakthroughs, being highly technical and somewhat arcane, are often overlooked by nonscientists. But it is a science with a unique history. Since ancient times, people have used the stars to help devise calendars, to navigate ships across oceans, to forecast the weather, and to foretell the future. Because stars and planets appear to revolve around the Earth, it took civilized man several thousand years of recorded observation to discover the truth behind that illusion.

It was not until the 16th century, when Nicolaus Copernicus suggested that the Earth revolved around the Sun, that astronomy in the modern sense began. He could not prove his assertions. That task lay ahead, for scientists like Tycho Brahe, Johannes Kepler, Galileo Galilei, and Isaac Newton. They could not have made progress without the aid of telescopes, invented during the early 17th century. From then on, a pattern emerged: Astronomical knowledge and instruments would advance together, aiding each other along the way. It is a pattern that continues today.

Here, James Trefil describes the history of the telescope, and the West's transition from skywatching to astrophysics. George Field explains the latest theories of star formation, the emergence of our solar system, and the structure and origin of the universe. And Eric Chaisson and Field discuss what man ultimately seeks from the stars.

# FROM ASTRONOMY TO ASTROPHYSICS

*by James Trefil*

Nicolaus Copernicus (1473–1543) was a Pole, a churchman, an intellectual recluse, and a somewhat enigmatic figure. Much is unknown about him, yet he sparked a scientific revolution that powerfully influenced the subsequent five centuries. Today, looking back at his life and work, it is difficult to comprehend the magnitude of the Copernican Revolution, how momentous a change it really was for 16th-century Europe. But altering civilized man's view of the cosmos is exactly what he did.

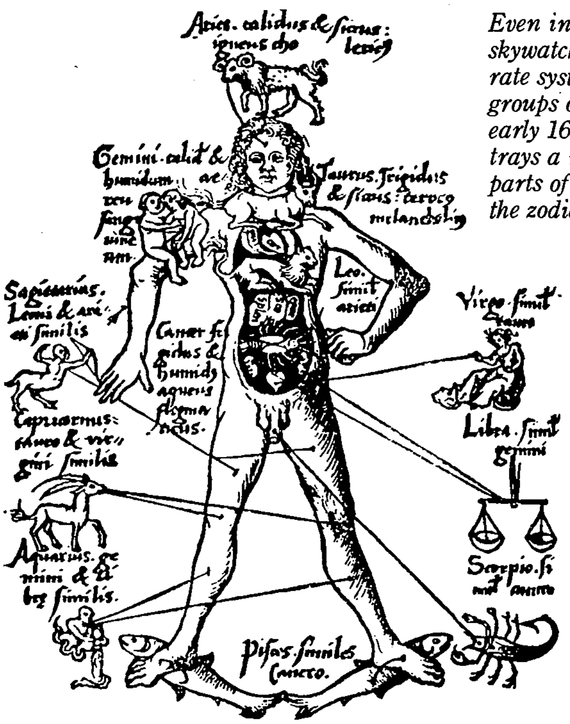
Guided by his uncle, a Roman Catholic bishop, Copernicus was elected to a position as canon (business manager) at the Cathedral of Frauenburg in his native Poland. He traveled widely, studied in Italy, and was a model scholar and churchman. From roughly 1512 on, he developed a scheme of a planetary system in which the planets moved and the Sun stood still. He confided his manuscript to a printer only in 1540, at age 67. As the story goes, he received a copy of his published book on the day he died, three years later.

The book, *On the Revolutions of the Celestial Spheres*, is an odd mixture of revolutionary and traditional ideas. Since Claudius Ptolemy (circa A.D. 100–178), the ancient Greek astronomer who advocated a geocentric model of the universe, Europeans had envisioned the Sun, stars, and planets embedded in concentric spheres around the Earth, with God, in effect, cranking the mechanism from the outside.

Copernicus realized that the daily motion of the stars across the sky resulted from the Earth's rotation, and that the complex motions of planets were the natural effect of their movement around the Sun. His system, of course, was not identical to the modern one. To account for the true planetary orbits, Copernicus had to put his planets on epicycles (small circles centered on the rims of larger ones). The centers of the larger circles lay not in the Sun, but at a point in space between the Sun and the Earth. Even if it could not be proved, his view had an immense allure for adventuresome minds.

Copernicus's scheme was only somewhat simpler than Ptolemy's, but it prompted astronomy students (at least from 1543 on) to realize that they could question traditional wisdom. Human reason was freeing itself from burdens of the past—another major step for Europeans who had just experienced the throes of the Reformation, Martin Luther's break with the monolithic authoritarianism of Rome.

Another consequence of the Copernican system—one often



*Even in medieval Europe, skywatchers developed elaborate systems for interpreting groups of stars. At left, an early 16th-century artist portrays a relationship between parts of the human body and the zodiac.*

overlooked—is that it expanded mankind's concept of the universe. Formerly, with a seemingly stationary Earth, the realm of the stars lay just beyond Saturn's orbit; the entire universe seemed only as big as the solar system. But with Earth orbiting the Sun, the stars had to be far away to appear stationary. In one fell swoop, Copernicus moved the Earth from the center and set it moving in a new heaven of wider horizons. He and Christopher Columbus were contemporaries. Each man revealed a new world to Europe—but Copernicus was charting a realm whose outer boundaries have yet to be discovered.

As it happened, *On the Revolutions of the Celestial Spheres* spread quickly throughout Europe, encountering far less ecclesiastical opposition than Galileo would later face. For one thing, Copernicus was well connected in the church. For another, the unsigned preface of his book presents the Copernican system as a mathematical exercise, not necessarily a statement about the real world. This pretension left plenty of maneuver room for theologians and scholars.

Among Copernicus's readers was the Danish nobleman Tycho Brahe (1546–1601), who had a lifelong obsession with measuring the heavens accurately. During the 16th century, observation was not much more accurate than it had been during the time of Ptolemy.

Tycho, born before the invention of the telescope, pushed the accuracy of naked-eye astronomy to its limit. He built astronomical instruments, such as a huge brass quadrant and a four-cubit sextant, to reduce errors associated with reading small scales. He compensated for the expansion and shrinkage of his brass instruments due to temperature changes, devising tables to correct for these effects. He even built an underground observatory to reduce wind vibrations.

In part, the quest for precision grew out of the desire to distinguish between the Copernican and Ptolemaic systems, and because people of the mid-16th century had witnessed some unusual events in the heavens. On November 11, 1572, for instance, a new star appeared in the constellation of Cassiopeia—one so bright that during the next month it could be seen in daylight. Repairing to his beautifully crafted instruments, Tycho took a series of readings. He established beyond a doubt that the object (now called Tycho's supernova) moved less than the most distant planet in the sky and was therefore beyond the sphere of the stars. This feat established the 25-year-old Dane as one of Europe's premier astronomers.

So impressed was King Frederick II of Denmark that he installed Tycho on the Baltic island of Hven and provided the money to construct the world's largest astronomical observatory. There Tycho built instruments and gathered data unprecedented in both volume and accuracy.

All was well, until Tycho ran afoul of Frederick's successor, Christian IV, over a number of issues—such as whether or not Tycho had the right to throw peasants into his private dungeon. So the astronomer packed up his data, instruments, and court jester, and quit Hven for the court of Emperor Rudolf II in Prague.

### Tycho's Undoing

All told, Tycho lived an unusual life. At an early age, he was kidnapped by his wealthy and childless uncle Jorgen, who raised him in a castle in Tostrup. Sent to the University of Copenhagen to study jurisprudence, Tycho—profoundly impressed by an eclipse of the Sun in 1560—instead spent his time studying the stars. Prone to emotional outbursts, at the age of 20 he dueled a fellow student over the question of who was a better mathematician. During the battle, Tycho lost a piece of his nose and had to wear a gold alloy prosthesis.

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Even his death was bizarre. At a banquet attended by much of Prague's nobility, he partook copiously of Bohemian beer. Not wishing to appear impolite—so the story goes—he ate and drank without excusing himself. Bladder stones may have been his undoing; he fell into a fever that night and died 11 days later.

Tycho's data tables went to an impecunious Austrian mathematician he had hired after his arrival in Prague—Johannes Kepler.

Kepler (1571–1630) was a mystic by nature. But, when confronted with all the data that Tycho had collected over a lifetime, he felt compelled to question some of his basic assumptions. Instead of trying to force Tycho's data into preconceived patterns, Kepler returned to the basics and considered which shapes best described the motions of the known planets.

## Galileo as Martyr

Kepler's results are stated in what are now known as Kepler's first and second laws of planetary motion. The first law says that a planet's orbit assumes the shape of an ellipse—rather than a circle—with the Sun at one focus; the second law indicates that planets move faster when near the Sun than they do when farther away. In other words, as a planet passes near to the Sun it "swings around," speeding up as it does so.

Kepler published these two laws in 1609. A third and final law was published in 1619, relating the length of a planet's "year" to its distance from the Sun. Thus it became possible to shed excess conceptual baggage that scientists had developed to justify a false notion, namely, that celestial objects move along circular orbits.

Following the observational work of Copernicus, Tycho, and Kepler, Galileo Galilei (1564–1642) was the first to study the sky through a telescope.

Ironically, Galileo is one of those men in history who is famous for the wrong reasons. Because of his notorious trial in 1633 by the Roman Inquisition he has, perhaps undeservedly, become enshrined as a "martyr of science." Legend has it that he stood alone as a champion of the heliocentric universe against the forces of dogmatism and authority. This is unfortunate, because Galileo did many other things during his lifetime that were worthy of lasting fame. He was, for example, the founder of modern experimental physics. He also made the first break with naked-eye astronomy by starting a systematic study of the heavens with a telescope. He was largely responsible for bringing the ideas of Copernicus to the attention of the intellectual community of 17th-century Europe. It was this seemingly heretical activity, of course, that eventually caused him to draw the attention of the Inquisition.

The son of a musician in Pisa, Galileo studied at the local univer-

### GOING BACK TO STONEHENGE

Today most people take the sky for granted. Not so the ancients. They used the sky as clock, calendar, navigational aid, and oracle.

Among the oldest observatories, according to British astronomer Gerald S. Hawkins, is Stonehenge—a series of concentric circles, marked by large stones, standing on a plain near Salisbury, England. In 1963, Hawkins argued that Stonehenge enabled skywatchers, perhaps as early as 3100 B.C., to mark the solstices (when viewed correctly, the Sun rises over a 35-ton Heel Stone), the lunar cycles, and eclipses. Similar ruins stand around the world, in places as disparate as Scotland, Kenya, and the central United States.

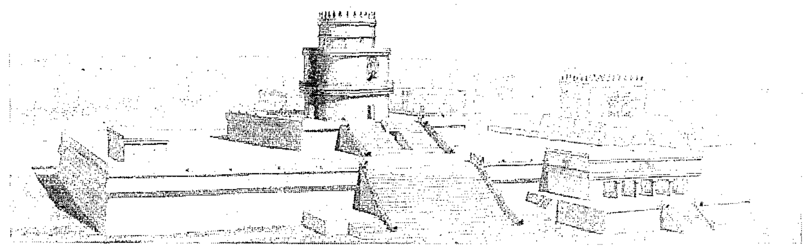
Cro-Magnon people were probably the first humans to note the stars. Animal bones with markings that correspond to lunar phases, dated 9,000 to 30,000 years old, have been found in Europe. Between 3000 B.C. and 2000 B.C., Babylonians in Mesopotamia devised the first systematic calendar, based on 235 lunar months (29.5 days apiece) in 19 solar years. Between 1646 and 1626 B.C., they made the first detailed astronomical records, and later (circa 400 B.C.) used mathematics to predict celestial events. They were astrologers too. Atop immense, stepped, mud-brick towers, such as the ziggurat of Ur in southeastern Iraq (construction began in 2100 B.C.), Babylonian priests prayed to the Moon god Nanna-Sin while surveying stars.

Ancient Egyptians also were stargazers. Many of their great monuments—such as the Great Pyramid of Cheops and the temple at Karnak—are aligned with key positions of the Sun, Moon, and stars. Yet, despite Egypt's creation of a "modern" calendar (12 30-day months, plus five extra days), the Babylonians surpassed the Egyptians in astronomical sophistication.

The Greeks were the first scientists, not only recording celestial motion but wondering why stars and planets moved along particular paths. They sought physical rather than religious explanations. Thales of Miletus (circa 585 B.C.) predicted eclipses; Pythagoras (circa 580–500 B.C.) and his school deduced that the Earth is round, and Eratosthenes of Cyrene (circa 276–194 B.C.) devised a method for measuring its circumference at the equator—250,000 stadia (the width of a stadium, 607 feet), a figure quite close to the actual 24,902 miles. By the second century A.D., Claudius Ptolemy summarized four

sity and embarked on a career teaching mathematics. As the story goes, his early interest in physics is associated with observations conducted at the Pisa cathedral. He noted that a cathedral lamp required the same amount of time to complete a swing no matter how wide the range of the swing. Later, Galileo suggested that this principle could be used to develop a pendulum clock. His studies of physics and mathematics helped him to win a position in the Medici court in Florence in 1610.

While in Venice in 1609, Galileo learned of the recent invention



*The Mayan Caracol of Chichén Itzá, as it may have appeared circa 1000* A.D.

centuries of Greek astronomy in his treatise *Almagest*. As early as 720 B.C., Chinese astronomers kept watch for "portentous" events: eclipses, comets, meteors, planetary alignments. But their observations were not "scientific"; they tended simply to record, not analyze, unusual phenomena.

In Central America, circa 1000 A.D., Mayan astronomers on the Yucatán Peninsula constructed an observatory, the Caracol of Chichén Itzá. It demonstrates in its architecture alone—through alignments with certain stars and planets—a knowledge of solstices, lunar cycles, and the motions of the Morning and Evening Star (Venus). Their astronomical records, detailed on the bark leaves of an almanac called the Dresden Codex (it is now in a Dresden museum), reveal great sophistication: They calculated the length of a 365-day solar year, a 29.5 day lunar cycle, and the cycles of Venus within minutes of their true periods.

Throughout North America, Indian tribes, too, practiced astronomy. Atop Medicine Mountain, in Wyoming's Bighorn Range, lies a circular arrangement of "loaf-sized" rocks. This "medicine wheel," in which 28 35-foot-long lines of rocks, seemingly spokes, reach out from a central hub to a surrounding circle of rocks, is believed to have been used for astronomical purposes. Similarly, the Hohokam Indian structure at Casa Grande near Phoenix, Arizona, contains 14 windowlike openings, eight of which are aligned with the rising and setting Sun during solstices and equinoxes. Other Sun-marking sites exist at Chaco Canyon, New Mexico, and Hovenweep, Utah. And, at Cahokia, Illinois, the American "woodhenge"—concentric circles comprised of 49 poles, with the largest circle measuring 410 feet across—is thought to have been a tool for measuring solstices and equinoxes, and possibly to predict eclipses.

of the telescope in the United Netherlands. He devised a superior lensmaking technique and produced a telescope capable of magnifying an image 32 times. It was an immense step forward. Astronomers could thereupon examine the heavens with more than the power of the unaided human eye. He opened a window on the cosmos and was not slow to exploit it.

During the years after the building of his telescope, Galileo and others saw many new things. Mountains loomed on the Moon where no mountains were supposed to be. The apparently unblemished Sun had spots. Venus was seen to go through phases as does the Moon. Galileo observed the four largest moons of Jupiter and caught a hint of Saturn's rings. As has happened ever since, whenever a new window on the sky is opened, the first glimpse shows an undreamed-of richness and complexity.

Why were these discoveries so important? The first two—lunar mountains and sunspots—showed that the Greek ideal of heavenly perfection was incorrect. Also, the fact that Venus could be observed to pass through Moonlike phases proved that at least one other planet orbited the Sun. And Jupiter's four moons belied the assumption that everything orbited Earth. These facts had enormous psychological impact during the 17th century.

## Enter Newton

Galileo announced the first of these findings in his book *The Starry Messenger*. He called Jupiter's satellites the Sidera Medici (Medicean Stars), attempting to flatter his hoped-for patrons, the Medici family. The ploy worked. He received support from Florence, and today those satellites are called the Galilean Moons.

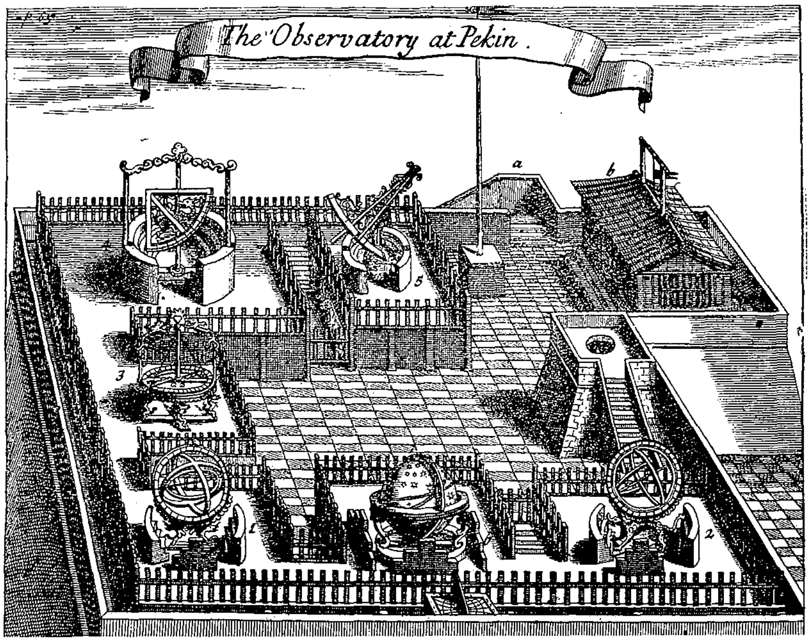
Furthermore, the maestro had a way with words, writing—unlike Copernicus and Kepler—in the vernacular, Italian in this case. Through his writings, Copernican ideas spread throughout Europe. Galileo's trial did not curb the spread of these ideas—indeed, its only effect was to guarantee that the center of astronomical studies would move across the Alps to the Protestant countries of Europe and eventually to England.

In the same year that Galileo died, 1642, Isaac Newton was born. It is a coincidence, of course, but one that symbolizes the continuity of the development of scientific ideas about the universe during the 17th century.

The scientific revolution of the 17th century culminated in the work of Isaac Newton, who developed a view of the universe still held today. His most important contribution to astronomy is the law of universal gravitation, which states that any two objects in the universe will experience a force of attraction proportional to their masses and to the distance between them. The laws that Kepler deduced from Tycho's data can also be derived from Newton's work.

In later years, a legend grew about how Newton realized that one gravitational law governed the entire universe. The part that sticks in the public fancy is the fall of an apple in an orchard.

To understand Newton's insight in that orchard, one must remember that, until his time, the science of astronomy and the science of mechanics (which dealt with the motions of things on Earth) were totally separated. No one had yet connected the stately turning of the planets with the fall of an apple on Earth. Newton's gift to humanity




*17th-century Chinese skywatchers at the Imperial Observatory observed the stars with astronomical instruments, some imported from Europe.*

was to show that such artificial distinctions do not hold in nature—that the universe is a single, seamless web, and that the forces guiding the Moon also cause apples to fall.

To demonstrate the unity of the gravitational force, Newton imagined what would happen if a cannon were placed on a mountaintop, firing successive projectiles, with an increase in the charge of each shot. Eventually, with just enough gunpowder, the cannonball would fly around the world, overcoming gravity's downward pull and maintaining a constant altitude.

This hypothetical missile, he concluded, was behaving like the Moon, or any other satellite. In his own words, "[I] compared the force requisite to keep the Moon in her Orb with the force of gravity at the surface of the Earth, and found them to answer pretty nearly." In effect, Newton had seen that the Moon and the Earth continually fall toward each other, offset by their orbital motion. With this realization, any simple distinction between terrestrial and celestial science—a notion accepted since ancient Greece—crumbled. Using calculus, a method that he originated, Newton worked out the planets' orbits and demonstrated that they followed Kepler's laws.

His vision of the solar system in perpetual motion led naturally to a model of the universe resembling a geared clock. Once the solar system had been created, its future history lay ordained. But a debate ensued along these lines: mathematician G. W. Leibniz argued that God had made an automated universe; theologian Samuel Clarke contended that God was continually adjusting the works. Either way, the Creator had more leisure than with Ptolemy's system, which ascribed to God (or appointed angels) the turning of cranks. Newton believed that God created a mechanistic universe and then fine-tuned the machinery while it operated.

It is difficult to overemphasize the importance of this new scientific movement, and of Newton's place as its prime mover. He completed the work begun by Copernicus and his successors.

In fact, the Newtonian Synthesis gave rise to another powerful idea: Events anywhere in the universe can be studied in laboratories on Earth. And, if nature's laws are constant, then all events of the past—right back to the creation of the universe—are accessible to investigation.

It is comforting, in the face of such advances in scientific knowledge, to reflect on how it all started. An obscure Polish scholar was able to set in motion a scientific revolution capped by, of all things, a view of space and time based on an inspired interpretation of a fallen apple in an English orchard.

## On to Mount Palomar

During the 200 years that followed Newton's discovery of the workings of the solar system, astronomers developed two improved tools. First, bigger, and sometimes better, telescopes allowed astronomers to collect more light from objects farther away. And second, improved theoretical tools, based on calculus and Newton's laws, enabled scientists to analyze (and therefore predict) the behavior of more complex celestial phenomena. The delicate interplay of instrumental and theoretical advances was like a waltz through history—first one partner would lead, then the other.

Galileo turned a primitive telescope toward the heavens. But to go beyond Galileo, it was necessary to build better telescopes. This was no easy task.

Newton saw no future in the type of telescope used by Galileo. Called the refractor, it uses a series of lenses to collect and focus incoming light. Unfortunately, it also suffers from a defect known as "chromatic aberration," in which colored fringes appear around an image's edges. Consequently, Newton built a telescope without lenses. Such a *reflector* telescope uses curved mirrors, made of polished metal, to focus light at the back of the instrument. However, his first models had little more power than did Galileo's refractor.

By the mid-18th century, techniques for fashioning mirrors from metal had been perfected. By the 20th century, mirrors were ground from glass and then coated with reflective metal. Today, such highly efficient light collectors are the workhorses of astronomy. The most famous (and most productive) of these giants is the 200-inch telescope located at the Hale Observatory on Mount Palomar near San Diego, California.

Completed in 1948, Hale's main mirror is 17 feet (five meters) across and weighs 14.5 tons. Technicians ground away more than five tons of glass from the original 20-ton disk to form a concave surface, which became reflective when polished and coated with a thin layer of aluminum. To construct the immense disk, molten Pyrex glass was poured into a form, then allowed to cool for eight months to keep the glass from cracking.

The telescope itself is so big that at one time an astronomer sat inside it to observe the stars. Today, however, a computer monitors observations. It is so well balanced that an electric motor no more powerful than one found in a food processor can rotate it. Although the Soviets now have a larger optical telescope operating in the Caucasus Mountains, technical troubles have limited its usefulness.

Improved telescope designs enabled astronomers to expand their inventory of the solar system. William Herschel (1738–1822), born in Germany, was a musician-turned-astronomer who lived in England during the 18th century. He built his own reflecting telescopes because he could not afford to buy one made by craftsmen. Believing that studying the heavens was one way to peer into the mind of God, Herschel set out to catalogue everything in the sky.

## Finding Neptune

On March 13, 1781, Herschel observed a fuzzy object, hitherto unknown. His telescope allowed him to see that this new object was not just a point (as most stars appear), but something with an extended structure. Since the object moved against a background of fixed stars, it had to be a planet or a comet. And, given that 2,000 years of skywatching had turned up only six planets, European astronomers looked carefully before concluding that Herschel really had found another planet—one located too far from the Sun to be seen by the naked eye. It was christened Uranus, and became the first planet discovered in modern times.

Astronomers throughout Europe worked to chart its orbit. It quickly became apparent that applying Newton's law of gravitation to the new planet did not give a correct description of its path in the sky. Working independently, an English and a French astronomer came to the same conclusion. In 1845, John Couch Adams and Urbain-Jean-Joseph Le Verrier showed that this orbital discrepancy could be explained if there were yet another planet beyond Uranus. On September 23, 1846, astronomers in Berlin saw it—the planet

## NEW EFFORTS IN ASTRONOMY

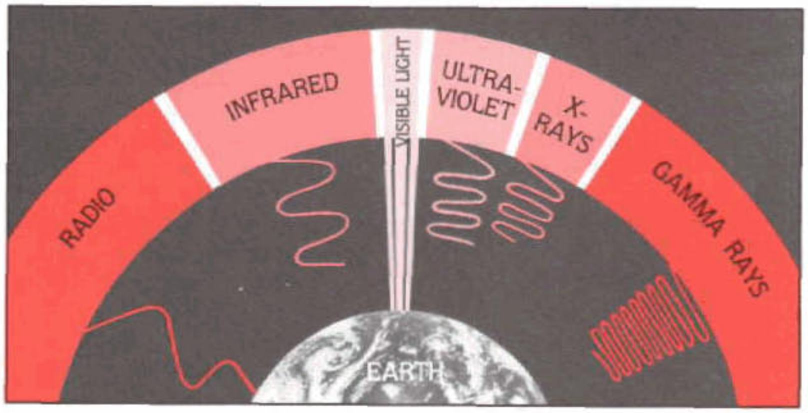
Since the discovery in 1932 that radio waves emanate from the Milky Way's center, astronomers have been scanning the "invisible" universe. That task requires special instruments. Because only visible light, radio waves, and some infrared radiation can penetrate the atmosphere, special devices are sent into space aboard satellites. Below, some details about the latest efforts to analyze specific kinds of electromagnetic radiation:

- RADIO WAVES (wavelength: one millimeter to 10 meters): The first radio telescope—a bowl-shaped antenna measuring 9.4 meters across—was built in Illinois in 1937. Today, "interferometry"—a computerized system that merges signals from an array of radio telescopes—allows astronomers to simulate one enormous dish. The Very Large Array in New Mexico synchronizes 27 radio telescopes to form images equivalent to those of one 24-kilometer dish. Currently, the National Science Foundation is building the Very Long Baseline Array; with 10 antennas spanning Hawaii to St. Croix, its "baseline" will measure 7,500 kilometers.
- INFRARED RADIATION (wavelength: one micron to one millimeter): Infrared radiation carries crucial data about star and planet formation. NASA's Kuiper Airborne Observatory, a 0.9 meter telescope aloft at 41,000 feet, has charted infrared sources since 1975. More impressive, the joint U.S.-Dutch-British Infrared Astronomical Satellite mapped more than 250,000 sources during 1983. On the drawing board for the 1990s are two space-based observatories: NASA's $600 million Shuttle Infrared Telescope Facility and the European Space Agency's Infrared Space Observatory.
- VISIBLE LIGHT (wavelength: 300 nanometers to one micron): Delayed because of space shuttle troubles, NASA's $1.5 billion Hubble Space Telescope awaits launch in 1988. Its 2.4-meter telescope will capture visible, infrared, and ultraviolet radiation, detecting objects 50 times fainter and seven times farther away than those detectable by Earth's best telescopes. Still, ground-based observatories with larger apertures remain important in spectral analysis. By the mid-1990s, Hawaii may house two giant optical telescopes; the $87 million Keck Telescope, using a honeycomb design, will join 36 mirrors into a single 10-meter mirror, while the proposed $125 million National New Technology Telescope will achieve a 15-meter aperture—the world's largest.
- ULTRAVIOLET RADIATION (wavelength: 10–300 nanometers). The

we now call Neptune.

While the discovery of Uranus depended on the development of better telescopes, the discovery of Neptune depended on the ability of theoreticians to predict the orbit of the new planet. In fact, once told of its general location, observers at Berlin took less than one night to pinpoint Neptune. The ninth planet, Pluto, was also found through computation and observation.

About the same time that Herschel was expanding our perception of the solar system, the return of a comet in 1758 as predicted




*A schematic diagram of the electromagnetic spectrum.*

first ultraviolet telescopes were hoisted aloft on high-altitude balloons. Today, the International Ultraviolet Explorer, a U.S.-European satellite launched in 1978, examines radiation from intergalactic matter and the outer layers of stars. Soon, NASA's Extreme Ultraviolet Explorer, now being developed, will study high-energy ultraviolet rays, so far uncharted.

- X-RAYS (wavelength: .01–10 nanometers). So energetic are x-rays that studying them requires a unique telescope design: cylindrical mirrors to deflect x-rays into focus. Between 1978 and 1981, the orbiting Einstein Observatory satellite used this method (as did its European counterpart, Exosat) to collect data on pulsars, neutron stars, and galactic nuclei. The latest x-ray space observatory is Japan's Astro-C, launched in February 1987 (approximate cost: $40 million). By 1995, NASA hopes to place in orbit the Advanced X-Ray Astrophysics Facility, a $1 billion telescope 100 times more sensitive than the Einstein Observatory.
- GAMMA RAYS (wavelength: less than .01 nanometers): Gamma rays are more energetic than x-rays, and difficult to measure. Thus the European gamma ray observatory, Cos-B, took seven years (1975–82) to make a gamma ray chart of the sky. In 1990, NASA plans to launch a $500 million space-based Gamma Ray Observatory, 10 times more sensitive than Cos-B, which will carry instruments supplied by the United States and Germany.

served to provide dramatic confirmation of the clockwork universe developed by Newton. In 1682, Edmund Halley (1656–1742) had observed a large comet approach the Sun and swing away. Looking at historical records, he found that a bright comet with roughly the same orbit had appeared in 1531 and 1607. Using Newton's laws and the positions of the planets, Halley calculated the orbit of the comet and predicted that it would again be near the Sun in 1758. Its appearance, on Christmas Day of that year, provided a major verification of Newton's description of the universe.

With telescopes and satellites routinely probing the farthest reaches of the universe, one would expect few surprises in the relatively mundane study of our own neighborhood in space. Not so. In 1978, scientists at the U.S. Naval Observatory in Flagstaff, Arizona, obtained high-grade photographs of Pluto, showing that the planet has a moon. It was christened Charon, after the boatman charged with conducting souls of the dead to the underworld, Pluto's realm. This discovery allowed astronomers to estimate the mass of Pluto, a value insufficient to explain all of the vagaries of the orbits of Neptune and Uranus. Thus, there still may be pages to be written in the story of the solar system—a possible 10th planet.

## Seeing the Spectrum

Beyond our own star system lie other stars, perhaps with their own planets. From a science concerned with determining *where* stars and planets are, the new discoveries changed the focus of astronomy to the question of *what* they are. A new science, astrophysics, emerged as a complement to astronomy. It seeks to reveal the nature of the stars through an understanding of the laws of physics.

The basis for this new departure in man's view of the heavens was a famous experiment by Isaac Newton. He noted that a glass prism held up to a beam of sunlight broke the light into its constituent colors—a "spectrum" of sunlight.

For a long time, this peculiar property of light was merely a nuisance to lensmakers. Then, in 1802, physician William Hyde Wollaston found narrow bands of missing color in the spectrum of sunlight. By 1814, a physicist, Joseph von Fraunhofer, made the first map of these lines, which now bear his name. Their origin remained a mystery until 1859, when Gustav Kirchhoff, working with Robert Bunsen at Heidelberg, showed that the lines were caused by familiar chemical elements in the Sun's outer atmosphere that absorb certain wavelengths of light.

Such "spectral analysis" works something like this: Each kind of element (e.g., hydrogen, nitrogen), when pushed to an "excited" state, emits a unique spectrum of light—a kind of atomic fingerprint. In fact, burning an element gives off a specific "emission spectrum," while passing light *through* an element causes certain colors to be absorbed, creating an "absorption spectrum." The correspondence between atoms and their unique spectra is daily evident: A neon light glows red; sodium-vapor street lamps emit yellow light; mercury-vapor lamps are bluish-white. Each element has its own colors.

Discovering this connection between atoms and light was enormously important. As early as 1868, bright lines were observed in the Sun's spectrum—lines that had no counterpart in any known element on Earth. Scientists concluded that a new element was present on the Sun, one that they named helium (from the Greek word for Sun, *helios*).

There was, as far as anyone could tell, no helium on the Earth. In 1895, however, helium was discovered in certain uranium-bearing minerals. Once again, it turned out that the Earth was not as different from the rest of the universe as some people had thought.

From these early days, the technique of identifying chemicals by their light spectra has penetrated every corner of modern technology. Spectroscopy is today used in industrial quality control (to monitor the presence of impurities), in medicine (to identify substances taken from the body), and in many other areas where one must determine the chemical constituents of materials. It even figures in courtroom dramas, where substances identified by this sort of analysis are accepted as legal evidence.

Once scientists had proven that known elements make up the Sun and other stars, another question arose: How could the stars shine so brightly for so long? Astrophysicists had calculated that, even if the Sun were made of pure anthracite coal, it could have shone for only 20,000 years—instead of the 4.5 billion years so far.

Throughout the last decades of the 19th century, scientists tried to determine the Sun's fuel source. The answer came from a completely unexpected quarter—the study of radioactive materials. By the 1930s, a number of things had become clear: First, certain nuclear processes alter the weight of atoms; second, the weight change is related to energy by means of Einstein's famous formula, $E = mc^2$. Arthur (later Sir Arthur) Eddington, working in England during the 1920s, had suggested that the conversion of mass to energy might be the process that provided the Sun's energy. But no one knew enough about nuclear physics at that time to consider Eddington's suggestion as anything more than an educated guess.

In fact, the Sun shines through a fusion process in which lighter elements are transmuted into heavier ones, liberating energy. Detailed knowledge of this phenomenon grew out of a small conference held in Washington, D.C., in April 1938. The gathering had aimed to unite astrophysicists and nuclear physicists. The former knew about stellar structure; the latter understood something of the reactions taking place in stars. The interchange must have been extraordinarily effective: Shortly thereafter Hans Bethe of Cornell University worked out the earliest model of fusion in stars.

The theory was so successful that Bethe was awarded a Nobel Prize for physics in 1967. His idea of nuclear reactions in our Sun allowed scientists to begin to understand the very fires of creation.

# THE UNIVERSE AND MAN

*by George B. Field*

What are stars? Why do those tiny points of light sparkle with different colors? How far away are they?

Astronomers use physics and mathematics to create new images of stars. For them, the delight of seeing stars on a clear, dark night is enhanced by searching for a unified understanding of the universe.

Key discoveries opened the study of the universe as a whole. At the beginning of this century, astronomers had a limited sense of the size of the universe. Then, in 1924, Edwin Hubble (1889–1953) proved that the Great Nebula—what appeared to be a cloud of gas in the constellation Andromeda at the edge of our galaxy—was actually an "island universe" far outside the Milky Way. Whereas the Sun is roughly 28,000 light years* from the center of the galaxy, it is two million light years from the Andromeda nebula. The Andromeda nebula and our galaxy are very similar with respect to size, shape, and luminous power. A giant wave propagates in the interstellar gas of each galaxy to form "spiral arms" that look like hurricane clouds.

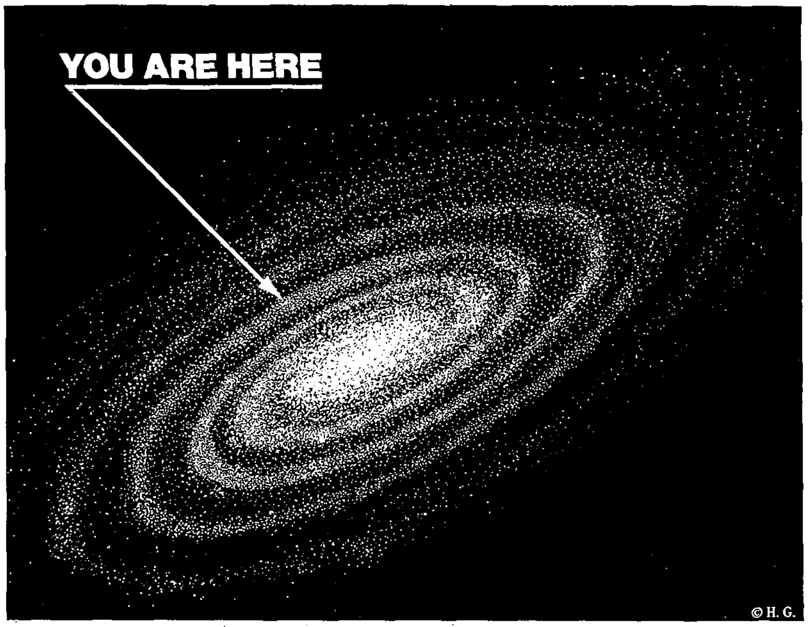
Beyond the Andromeda nebula, there are thousands of spiral galaxies like it, as well as galaxies of another kind, called elliptical galaxies. Galaxies tend to form groups of a dozen or so, and clusters of a thousand or more. The clusters are not isolated in space, but are connected by large sheets of matter composed of hundreds of small groups of galaxies.

The motion of a galaxy can be determined from the wavelengths of its spectral lines. In any given cluster, galaxies move at up to a thousand kilometers per second with respect to one another. Clusters would disintegrate were it not for the gravitational attraction of the matter in the cluster. This effect enables one to calculate the masses of clusters. While it might be expected that the masses of clusters are equal to the sum of the masses of the visible galaxies in them, there is at least 10 times as much invisible matter in clusters of galaxies as there is visible matter.

All groups and clusters of galaxies are receding from us, so the entire universe is expanding. In 1929, Hubble discovered that the velocity of a group or cluster is proportional to its distance from us, increasing by between 16 and 32 kilometers per second for each million light years of distance.† The most distant known clusters

*A light year is the distance that light, or any form of electromagnetic radiation, travels in a year—roughly 10 trillion kilometers.

†This velocity, called the Hubble constant, is difficult to determine and is not accurately known.




*An artist's conception of the Milky Way galaxy. The arrow designates the Sun. This drawing is based on a photograph of M31 Andromeda, a nearby spiral galaxy believed to look very much like the Milky Way.*

recede from us at more than half of the speed of light; one known galaxy is receding at 92 percent of the speed of light.

The radiation of even more distant objects, presumably moving extremely close to the speed of light (299,792 kilometers per second), shifts to such long wavelengths that those objects are almost impossible to detect. The region out to this point is referred to as "the observable universe"; its radius is 10 to 20 billion light years.

What is the universe made of? It is apparent that the visible matter of galaxies is largely stars. The Sun and stars are made of hydrogen and helium gases, along with much smaller amounts of heavier chemical elements like carbon, oxygen, silicon, and iron. Astronomers can understand the sizes, luminous powers, and temperatures of stars in terms of what happens when a large mass of gas slowly contracts, releasing gravitational energy, both heating the center of the star and causing it to radiate. When the central temperature reaches about 10 million degrees, hydrogen nuclei begin to combine to form helium nuclei, releasing nuclear energy that compensates for the loss of radiation, so the star ceases to contract and settles down for millions, or even billions, of years.

The ordinary matter that constitutes the Earth, Sun, and stars is made up of chemical elements, whose nuclei carry a positive electrical charge together with corresponding numbers of negatively charged electrons. There may also be "strange matter" in the universe, another kind of matter that has not yet been detected in terrestrial laboratories.

Is the invisible matter in galaxies just ordinary matter that emits very little radiation, perhaps because it exists in the form of very faint stars? There are several theories.

In 1922, Russian mathematician Alexander Friedmann (1888–1925) worked out models for the universe, according to which four-dimensional space-time* is curved by the effects of gravitation. The more matter there is in space, the greater its gravitational effect and the greater the curvature of space-time. If there is a critical density of roughly $10^{-29}$ grams of matter per cubic centimeter, then the universe is described by a special Friedmann model in which it is infinitely large and forever expanding, but expanding with ever-decreasing speed. If the amount of matter is less than this critical value, then space is curved outward and also expands forever, but with constant speed. If the amount of matter is greater than the critical value, then space is curved inward and its volume is finite.

In this last model, the gravitational force continually reduces the expansion velocity, ultimately reversing the expansion and causing the universe to collapse. All of the Friedmann models start with a "big bang" at the origin of time, when the universe was infinitely compressed. From the rate of expansion, this must have occurred 10 billion to 20 billion years ago.

## Expansion of the Universe

Friedmann models are supported by astronomical evidence, including Hubble's discovery of the expansion of the universe. In 1965, there was further confirmation when Arno Penzias and Robert Wilson discovered faint cosmic background radiation, left over from the big bang, at radio wavelengths. That radiation is shifted into the radio band by the expansion of the universe.

During the 1940s, George Gamow (1904–68) and his collaborators reasoned that the highly compressed matter of the big bang must have been hot; at 100 seconds after the big bang, the tempera-

*The term "space-time" refers to Albert Einstein's demonstration of the fact that space and time are not distinct entities. Rather, they are inextricably linked in a single four-dimensional continuum.

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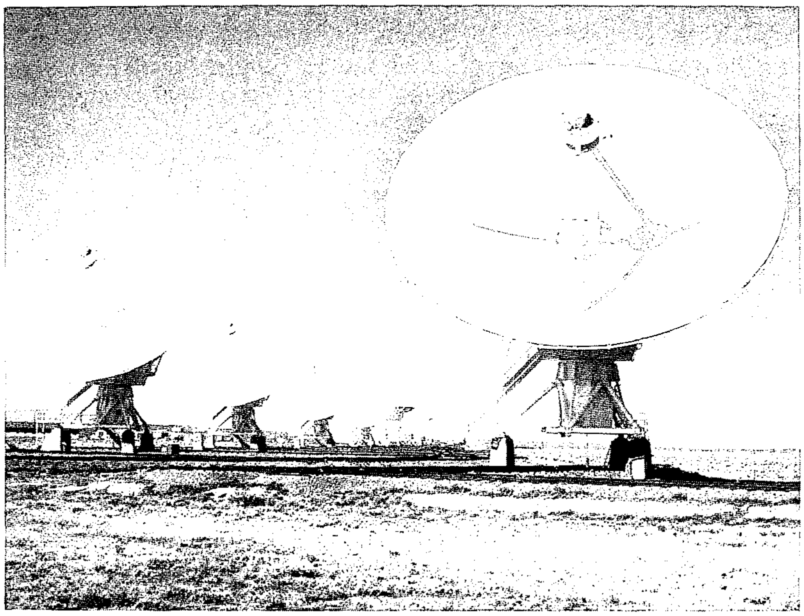


*The Very Large Array, located near Socorro, New Mexico, consists of 27 25-meter reflector antennas, arranged in a Y-shaped pattern. Two arms are 13 miles long, the third is 11.8 miles long.*

ture would have reached one billion degrees, so hot that atomic nuclei would readily react with one another to form new chemical elements. The predicted amounts of the light elements (hydrogen, helium, and lithium) produced during the first three minutes depend on the amount of ordinary matter at that time. The observation of the intensity of the background radiation, combined with measured abundances of light elements, leads, via the theory of nuclear reactions, to the estimate that the density of ordinary matter in the universe is only $10^{-30}$ grams per cubic centimeter—about 10 percent of the critical density in the Friedmann models.

In 1981, Alan Guth pointed out that if Grand Unified Theories (GUTs)* of elementary particles are correct, then the behavior of the extremely early universe could have differed dramatically from the Friedmann model for a very short time. Some $10^{-35}$ seconds after the creation, when the temperature was $10^{27}$ degrees, the universe would have suddenly "inflated" by a factor of at least $10^{20}$, thereafter resuming its Friedmann expansion. Inflation predicts that the amount

*Since the early 20th century, physicists have been attempting to find an overarching theory that links such disparate forces as gravity, magnetism, and the nuclear binding forces. To date, no GUT has been perfected.

of matter in all forms must equal the critical value. Since ordinary matter contributes only 10 percent of that critical value, strange matter must make up the other 90 percent. Grand Unified Theories also predict that particles (such as axions or photinos) can exist that could constitute the required strange matter.

The big bang involved densities and temperatures far beyond those obtainable in the laboratory, but it happened long ago. The universe still behaves wildly at certain times and places. Some elliptical galaxies that appear normal in photographs, such as Messier 87 in the Virgo cluster of galaxies, are sources of radio emission. A tiny but powerful energy source lurks in the center of the galaxy, shooting out jets of fast particles that are detected by radio astronomers.

### Extreme Conditions

During the 1960s, radio astronomers noticed pulses coming repeatedly from one part of the sky. Today hundreds of "pulsars" are known. They are explained by the rotation of a star on which a "hot spot" emits radiation into a small part of the sky, so that a pulse is seen each time the hot spot comes into view. The times between pulses are usually only a few seconds. A star like the Sun would fly apart if it rotated that fast, and even the compact white dwarf stars (to which most stars contract in the course of their evolution) would fly apart, so pulsars are neither ordinary stars nor white dwarfs. But neutron stars, made of nuclear matter from which all energy has been removed in the course of stellar evolution, are much more compact and stable, and can withstand the rapid rotation required to explain pulsars. It is believed that the collapse of the inner part of a star to form a neutron star is the cause of the stellar explosions observed as supernovas. Indeed, there is a pulsar in the Crab Nebula spinning 33 times per second, the remains of a stellar explosion in A.D. 1054 that was observed by Chinese court astronomers.

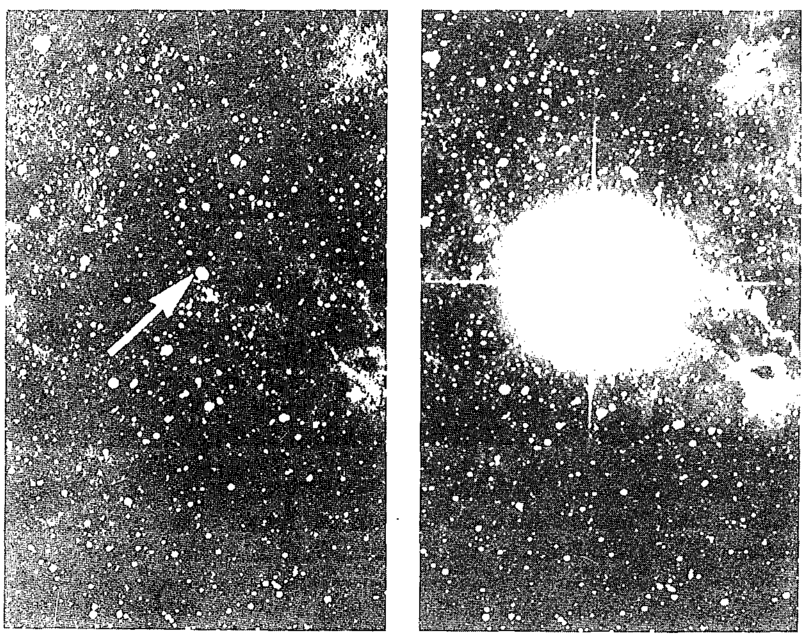
When nuclear fuel is exhausted, the core of a massive star collapses to form a neutron star weighing 1.4 times as much as the Sun; its radius is only a few kilometers. The energy released in a fraction of a second by the gravitational compression of matter is in the form of elusive particles called neutrinos. Some of them are absorbed by the layers above, heating them to about a billion degrees and causing a whole variety of reactions to occur among the atomic nuclei present. When this matter is flung into space, it contains heavy elements in agreement with the amounts observed in the galaxy.

If the core of a star that has run out of fuel is more massive than a neutron star, then it cannot resist the inward pull of gravitation, and collapses to a point. Near it, space-time is so curved that light rays actually bend back upon themselves and spiral into the star. The complete lack of all radiation from such an object is the basis for its much-publicized name, "black hole."

X-ray astronomers have found sources in which a compact star in orbit around a normal star steals gas from it, heating the gas enough to emit x-rays. One can deduce the mass of the compact star. In several cases, the result is 1.4 times the mass of the Sun, agreeing with the theoretical prediction for neutron stars. But in three known unusual x-ray sources, the mass of the compact object is much greater than that of a neutron star, so it must be a black hole. As a black hole steals gas from its companion, it draws the gas into a tight orbit around the black hole, moving at nearly the speed of light. Friction heats the gas to x-ray temperatures, and this attracts the attention of astronomers just before it plunges into the black hole.

In order to account for the huge amounts of radiation observed from the centers of active galaxies, one needs a mass so large that it would inevitably collapse to form a black hole. Active galaxies behave somewhat like stellar x-ray sources. A black hole in an active galaxy has a mass 100 million times greater than that of the Sun, and produces correspondingly large amounts of energy.

Typically, each cubic centimeter of interstellar space contains about one atom or molecule, but the distribution of gas is far from



*"Before" and "after" photographs of stars in the Large Magellanic Cloud, 163,000 light years from Earth, where astronomers in Chile noted a supernova on Feb. 24, 1987. The "before" picture was taken three years ago.*

uniform. Much of the volume is taken up with extremely tenuous gas heated to nearly a million degrees by supernova explosions, but there are dense clouds of gas that have temperatures only 10–100 degrees above absolute zero.* In these clouds, hydrogen atoms are combined into $H_2$ molecules. Scattered throughout the clouds are dust particles only 1/100,000 of a centimeter across, detected as they scatter and absorb the light from stars beyond them. They appear to have cores of ordinary rock, surrounded by mantles containing relatively light and abundant chemical elements, such as carbon, nitrogen, oxygen, and hydrogen.

In the densest clouds, interstellar gas and dust are gravitationally collapsing onto various centers of attraction. The distances involved—light years—are enormous, so collapse takes millions of years. Current measurements suggest that the final result will be the birth of a new star. Hundreds of new stars may be born from the collapse of a single cloud.

Our own star, the Sun, was born this way about 4.5 billion years ago, when an interstellar cloud was momentarily squeezed to higher density by the pressure of a nearby supernova explosion, initiating its collapse. Just as a figure skater spins more rapidly as she draws in her arms, the collapsing cloud began to rotate more rapidly. Collapse toward the axis of rotation slowed down but continued, and eventually a disk of gas was formed. The gas at the center became the Sun, and the disk became the birthplace of the planets.

### The Solar System

The dust drifted through the gas toward the midplane of the disk, enriching the medium to the point that the dust particles began to collide and stick to one another. The large particles collided in turn, until finally bodies a kilometer across had accumulated. These bodies collided with each other and stuck, building up to about the size of the inner planets (Mercury, Venus, Earth, Mars) and the cores of the outer planets. The giant planets of the outer solar system (Jupiter, Saturn, Uranus, Neptune) gravitationally attracted additional material from the surrounding medium, becoming much larger than the inner planets.

The decay of radioactive elements incorporated in the inner planets slowly heated their interiors to the melting point. Heavy materials like iron flowed to the center, while volatile materials composed of hydrogen, carbon, nitrogen, and oxygen were vaporized, coming to the surface in the form of gases such as molecular hydrogen, water vapor, carbon dioxide, methane, and ammonia. These gases escaped from Mercury, as it is so close to the Sun that its

*Absolute zero, or 0° Kelvin, is equal to -273° Celsius. It is the temperature at which matter has no thermal energy.

## RESEARCH: DOLLARS AND PEOPLE

Studying the stars is a costly affair.

For 1987, the U.S. Congress allocated roughly \$514 million for astronomy research; most dollars will go to the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF). NASA will spend \$402 million, largely on satellite projects, including the Hubble Space Telescope (annual cost: \$98 million) and the Gamma Ray Observatory (\$49 million). The NSF, with a modest \$80 million budget, will finance research and the operation of ground-based observatories, such as the Very Large Array near Socorro, New Mexico, and the National Observatories at Kitt Peak, Arizona, and Green Bank, West Virginia. Some private organizations also support astronomy. One example: the Keck Foundation, which in 1985 donated \$70 million to build a 10-meter optical telescope in Mauna Kea, Hawaii.

The United States is the biggest spender on astronomy, but not the only spender. The European Space Agency (ESA), a consortium of European programs, spent \$107 million for space science in 1986. ESA's science budget is only a fraction of NASA's (one-seventh in 1985), limiting the Europeans to one medium-sized project every two years; nevertheless, it produces first-rate results, such as its 1986 Giotto mission to intercept Halley's comet. Moreover, several European nations allot additional money for home-based astronomical research. Outlays for 1982: France, \$31.5 million; Great Britain, \$12.1 million; Holland, \$6.3 million; and West Germany, \$5.8 million. In 1985, Japan's Institute of Space and Astronautical Sciences devoted \$70 million to astronomy, recently launching Astro-C, an x-ray mission. Although the USSR outspends America on space programs (including military outlays), Moscow's financial commitment to astronomy is less than Washington's. Yet the Soviets do maintain several ground-based observatories, including large telescopes at Zelenchukskaya and Pulkovo. And Soviet satellite astronomy has burgeoned since 1982, when Salyut-7 carried aloft two French astronomical instruments. Among the USSR's more elaborate projects is ASTRON, a joint French-Soviet ultraviolet and x-ray satellite launched in 1983.

Why is there so much American interest in astronomy? For one thing, the United States is home to more than 3,000 professional astronomers and an estimated 250,000 amateurs, according to the U.S. Astronomical League. Of the professionals, one-third obtained their doctorates during the 1960s. Today there is a glut—more trained astronomers than available jobs. But it is a "graying" profession, and, at least according to one University of Wyoming study, the late 1990s will see a shortage of trained astronomers.

Nowadays American astronomers perform research by committee, lobby for funds from Congress, and manage large-scale staffs. In doing so, they are acquiring a high-tech image, observe astrophysicist Wallace Tucker and Karen Tucker. No longer does the public view the contemporary astronomer as "a solitary person shivering through the night in a lonely vigil at a telescope on some desolate mountaintop."

surface is too hot to retain them, but Venus, Earth, and Mars did retain them. In trying to understand the origin of life, it is of great interest to know how the atmospheres of these three planets evolved.

Earth's temperature allowed water to condense as a liquid, forming the oceans. Carbon dioxide in the atmosphere then dissolved in the oceans, and combined with minerals to form limestone, thus limiting the carbon dioxide in the atmosphere to low levels. Because Venus is closer to the Sun, its temperature remained above the condensation point for water, and carbon dioxide remained in the atmosphere. Because carbon dioxide absorbs infrared radiation emitted by a planetary surface heated by the Sun, the surface temperature rose. In the case of Venus, it is high enough to melt lead.

On Mars, the amount of carbon dioxide is too small for this to be a significant effect, and because of Mars's greater distance from the Sun, the temperature is so low that water remains frozen. The fact that water is liquid was crucial for the origin of life, as the chemical reactions involved took place in aqueous solution.

## Life on Earth

It is believed that ultraviolet light from the Sun broke the molecules in Earth's atmosphere into smaller pieces—such as OH, CO, and NH—that reacted with each other to form more molecules, like hydrogen cyanide (HCN) and formaldehyde ($H_2CO$), which then dissolved in seawater. With the ebb and flow of tides over millions of years, some of these molecules were deposited on the surfaces of rocks in tidal pools. On rocks having specific surface structures, the warming by sunlight polymerized the molecules to form such complicated molecules as amino acids, nucleic acids, sugars, and bases. One of the nucleic acids, adenine, combines with phosphates dissolved in water to form ATP (adenosine triphosphate). This molecule is rich in energy, and today is used by living organisms to transport energy from place to place.

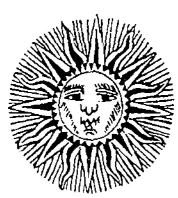
Nucleic acids, together with bases, sugars, and dissolved minerals, polymerized to form DNA, the molecule containing the genetic code. Fatty acids dissolved in the seawater coalesced to form minute droplets, thereby concentrating other molecules enough to permit further reactions among them. DNA began to use the energy supplied from sunlight by ATP to build up protein molecules from amino acids. Most of the proteins were useless, but in rare instances they reinforced the structure of the droplet, enabling further reactions. In this way the DNA could effect its own survival. A handful of "successful" DNA molecules were able to replicate themselves, thus initiating the process of biological reproduction. This is one idea as to how the first cells were created from nonliving matter.

The big bang, inflation of the universe, the origin of matter, the formation of the light elements, the formation of our galaxy, the synthesis of heavy elements in supernova explosions, the coalescence of materials to form interstellar dust, the collapse of a cloud to form the solar system, the formation of the individual planets, the origin of the oceans and atmosphere of Earth, and specific chemical processes all preceded the origin of life.

There is no reason to think that any of these processes differed dramatically anywhere in the universe, so our solar system is probably not unique. There could well be other "Earths" where the temperature is moderate and water is in liquid form. Could there not be life on these planets, and even intelligent life as well?

Today astronomers study the evolution of the universe by literally looking back in time. Taking advantage of the fact that light travels at a finite speed, we observe everything as it was in the past. An image of Uranus, radioed back by the Voyager II spacecraft, reveals the state of that planet as it was over two hours ago. A large telescope reveals the state of a distant galaxy 100 million years ago. The hiss of the cosmic microwave background radiation reveals the state of the universe 10 billion to 20 billion years ago. Sometime between then and now, galaxies formed out of primordial gas, the first stars formed and supernovas exploded, the first planets were formed from the fresh heavy elements, and the first life originated.

If these processes really are universal, they probably occurred in an orderly time sequence. If astronomers had instruments of unlimited power at their disposal, they would see galaxies forming at enormous distances, while, at somewhat smaller distances, the first stars and supernovas could be seen. Finally they would find a sphere a few billion light years away where life emerged. The Milky Way galaxy has already traveled this path all the way to the evolution of intelligence, so the universe has, in a sense, become aware of itself. Is it surprising that some of us are intrigued by the stars?



# BEYOND ASTRONOMY

*by Eric J. Chaisson and George B. Field*

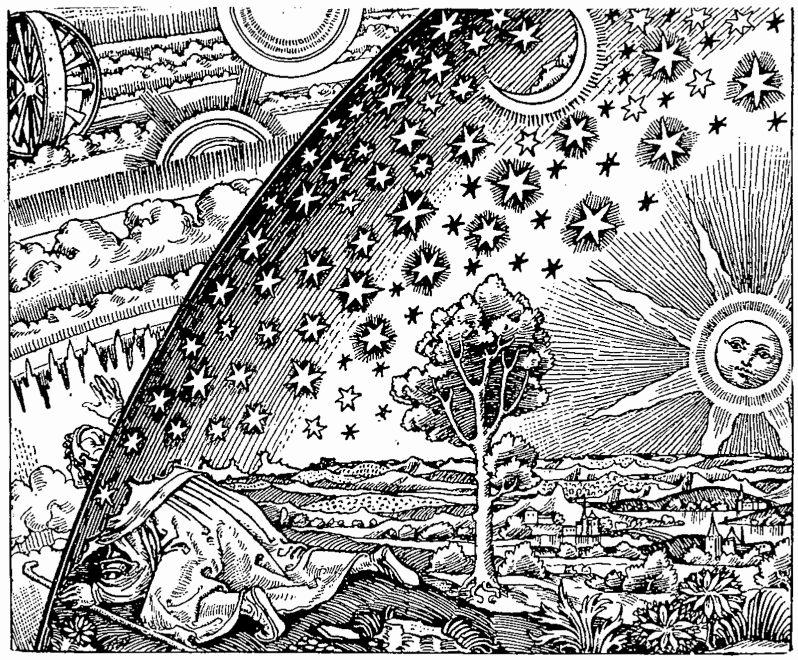
> You see then, studious reader, how the subtle mind of Galileo, in my opinion the first philosopher of the day, uses this telescope of ours like a sort of ladder, scales the furthest and loftiest walls of the visible world, surveys all things with his own eyes, and, from the position he has gained, darts the glances of his most acute intellect upon these petty abodes of ours—the planetary spheres I mean,—and compares with keenest reasoning the distant with the near, the lofty with the deep.
>
> *From* Dioptrics *by Johannes Kepler, Augsburg, 1611.*

Nature offers no greater splendor than the starry sky on a clear, dark night. Silent, timeless, jeweled with the constellations of ancient myth and legend, the night sky has inspired wonder throughout the ages—a wonder that leads our imaginations far from the confines of Earth and the pace of present day, out into boundless space and cosmic time itself.

Astronomy, born in response to that wonder, is sustained by two of the most fundamental traits of human nature: the need to explore and the need to understand. Through the interplay of curiosity, discovery, and analysis—the keys to exploration and understanding—answers to questions about the universe have been sought since the earliest times, for astronomy is the oldest of the sciences. Yet, not since its beginnings has astronomy been more vigorous or exciting than it is today.

Indeed, we are at the dawn of a new age in space science. Astronomy no longer evokes visions of plodding intellectuals peering through long telescope tubes. Nor does the cosmos any longer refer to that seemingly inactive, immutable regime captured visually by occasionally gazing at the nighttime sky. Modern astrophysics now deciphers a more vibrant, evolving universe—one in which stars emerge and perish like living things, galaxies spew forth vast quantities of energy, and life itself is understood as a natural consequence of the evolution of matter. Yet, amid the cosmic symphony of visible and invisible matter strewn across the universe, we humans seemingly play no special role. The rock called Earth is merely a platform on which to develop new technologies and sciences, all of which tend to reinforce the magnificent mediocrity of human life in the universe.

New discoveries always not only advance knowledge, but also raise new questions. Astrophysicists will encounter many new prob-



*Man attempts to peer beyond the confines of Earth's skies—a classic theme here depicted by artist Camille Flammarion in a 19th-century woodcut.*

lems in the decades ahead, but this should neither dismay nor frustrate us, for this is precisely how science operates. Each discovery adds to our storehouse of information, generating a host of questions that lead in turn to more discoveries, and so on, resulting in a rich acceleration of basic knowledge.

Through modern astronomical research, we now realize that we are connected to distant space and time not only by our imaginations but also through a common cosmic heritage: Most of the chemical elements comprising our bodies were created billions of years ago in the hot interiors of remote and long-vanished stars. Their hydrogen and helium fuel finally spent, these giant stars met death in cataclysmic supernova explosions, scattering afar the atoms of heavy elements synthesized deep within their cores. Eventually this matter collected into clouds of gas in interstellar space; these, in turn, slowly collapsed to give birth to a new generation of stars. In this way, the Sun and its complement of planets were formed nearly five billion years ago. Drawing upon the matter gathered from the debris of its stellar ancestors, the planet Earth provided the conditions that ultimately gave rise to life. Thus, like every object in our solar system,

## EXTRATERRESTRIAL LIFE?

In 1894, Boston astronomer Percival Lowell titillated America with his "proof" that life exists on Mars. Telescope images of channels on Mars's surface, he argued, were evidence of a Martian civilization.

There is no life on Mars. But there might be life elsewhere.

Though often regarded as the province of dreamers (or Hollywood producers), the Search for Extraterrestrial Intelligence (SETI) is a serious scientific enterprise. In 1982, Congress authorized the National Aeronautics and Space Administration (NASA) to spend $1.5 million on SETI—a big turnaround, since Congress had previously scuttled SETI.

*E.T.*

Why the reversal? One factor was *Astronomy and Astrophysics for the 1980s*, a report issued in April 1982 by the National Academy of Sciences recommending a SETI program. Then, in August 1982, the International Astronomical Union created a SETI commission. In addition, 68 scientists from 12 nations published a SETI Manifesto, calling for "a coordinated, worldwide, and systematic search for extraterrestrial life." As a result, for fiscal 1987, NASA will spend roughly $2.2 million on SETI.

Proponents of SETI argue that, since life *did* evolve on Earth, it probably has done so elsewhere. The best estimates indicate that roughly 10 million stars in the visible universe have planets that potentially could support life.

To find out if anyone is out there, in 1959 astronomers Giuseppe Cocconi and Philip Morrison proposed listening for extraterrestrial radio signals. Then, in 1960, Cornell astronomer Frank Drake first eavesdropped on two nearby stars, Tau Ceti and Epsilon Eridani—but to no avail. By 1973, Ohio State University had begun round-the-clock monitoring of extraterrestrial radio signals, on 50 channels. Today, the Harvard-Smithsonian Project Meta uses an 84-foot radio telescope at Massachusetts's Oak Ridge Observatory to scan eight million radio channels. And, at the University of California, Berkeley, astronomers are searching 128,000 radio channels "piggybacked" from other experiments at the National Radio Astronomy Observatory in West Virginia.

On the SETI drawing board: NASA's "multi-channel spectrum analyzer." If built, it will monitor 10 million radio channels as part of the Microwave Observing Project. The total cost: $70 million over 10 years.

A few astronomers are even sending out messages to distant galaxies. In 1974, astronomers at Arecibo, Puerto Rico, transmitted signals to the Great Cluster of Hercules, 21,000 light years away. (A reply is expected in 42,000 years.) Even the Pioneer 10 and 11 and Voyager I and II space probes, launched during the 1970s, carried "greeting" plaques, solar system maps, and video disks. But such "shots in the dark" are not popular. Why? Most astronomers, says Berkeley's Stuart Bowyer, prefer projects that "bear fruit during their lifetimes."

each living creature on Earth embodies atoms from distant realms of our galaxy and from a past far more remote than the beginnings of human evolution.

Although ours is the only planetary system we know for sure, others may surround many of the hundreds of billions of stars in our galaxy. Elsewhere in the universe, beings with an intelligence surpassing our own may also at this moment gaze in wonder at the nighttime sky, impelled by even more powerful imaginations. If such beings exist—possibly even communicating across the vast expanses of interstellar space—they, too, must share our cosmic heritage.

Emerging largely from our studies of the invisible universe, this recognition of our cosmic heritage is a relatively recent achievement in astronomy. However, it is but one of many such insights that our generation alone has been privileged to attain. Indeed, our descendants will likely regard our generation as the one that broached the electromagnetic spectrum beyond visible light, thus not only providing a whole new glimpse of our richly endowed universe, but perhaps more significantly recognizing life's integral role in the cosmos.

In all of history, there have been only two periods in which our perception of the universe has been so revolutionized within a single human lifetime. The first occurred nearly four centuries ago at the time of Galileo; the second is now under way.

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# BACKGROUND BOOKS

## ASTRONOMY

Human beings have long endeavored to form a coherent picture of the universe—as much of it as any age could fathom—and of man's place in it.

That picture began to take shape during the end of the Ice Age, perhaps as long as 30,000 years ago, according to Evan Hadingham in **Early Man and the Cosmos** (Univ. of Okla., 1985). Moving with ease from Eskimo moonwatchers to Pueblo Indian sunwatchers, he provides a colorful chronology and comparisons of a dozen primitive skywatching societies.

Two similar treatments, James Cornell's **First Stargazers** (Scribner's, 1981), and **Astronomy of the Ancients** (MIT, 1981), edited by Kenneth Brecher and Michael Feirtag, expand on astronomy's archaeological aspects. In addition to describing ancient Egyptian and Babylonian astronomy, Cornell explains the relevance of specific ancient observatories in the Far East and Africa; Brecher's and Feirtag's collection of eight essays by leading archaeoastronomers focuses on such matters as the first scientific instruments and the medicine wheels of the Plains Indians. Providing a close look at particular cultures, **Native American Astronomy** (Univ. of Tex., 1979), edited by Anthony F. Aveni, and **At the Crossroads of the Earth and the Sky: An Andean Cosmology** (Univ. of Tex., 1981) by Gary Urton suggest that the term "primitive" does not always fit early societies.

The invention of specialized tools, such as telescopes, has played a crucial role in the evolution of astronomical knowledge. Focusing on the relationship between theoretical and technical advances in astronomy, Cornell's Martin Harwit, in **Cosmic Discovery: The Search, Scope, and Heritage of Astronomy** (MIT, 1984), shows how theories and instruments tend to improve together. Using charts and graphs, he demonstrates the rapid progress in astronomy since World War II, noting, among other things, the major astronomical discoveries by people not trained as astronomers—physicists, chemists, engineers, and even theologians.

What are those discoveries? By far the best way to comprehend the majesty of the cosmos, and to understand what astronomers have found, is to see what they see. **The Cambridge Atlas of Astronomy** (Cambridge, 1985), edited by Jean Audauze and Guy Israël, provides 432 pages of color photographs, charts, and diagrams of objects millions of light years from Earth. Included: Venus's landscape, Jupiter's moons, the Magellanic Clouds, gaseous nebulae, clusters of galaxies, neutron stars, and pulsars. **The Cambridge Photographic Atlas of the Planets** (Cambridge, 1982), edited by Geoffrey Briggs and Fredric Taylor, and **Colours of the Stars** (Cambridge, 1984) by David Malin and Paul Murdin, supply greater detail.

Many of these spectacular images are products of recent journeys into space. Indeed, **Astronomy from Space: Sputnik to Space Telescope** (MIT, 1985), edited by James Cornell and Paul Gorenstein, provides 10 essays by research astronomers on such topics as exploration of the Moon, ultraviolet and x-ray charting of the sky, the geology of the planets, and the future of space astronomy. Wallace Tucker's and Karen Tucker's **Cosmic Inquirers** (Harvard, 1986) describes the difficult technical labor that goes into designing and carrying out big expensive projects, such as the construction of the Very Large Array in New Mexico or the launching of the Einstein X-Ray Observatory.

The fruits of these and other large-scale research projects are well illustrated (240 pages of color plates) in **The New Astronomy** (Cambridge, 1983) by Nigel Henbest and Michael Marten. Equally useful summaries are Paul W. Hodge's **Galaxies** (Harvard, 1986), James Elliot's and Richard Kerr's **Rings: Discoveries from Galileo to Voyager** (MIT, 1984), and Wallace Tucker's and Riccardo Giacconi's **X-Ray Universe** (Harvard, 1985).

Closer to home, **The Milky Way** (Harvard, 1941, 1981) is Bart J. Bok's and Priscilla F. Bok's classic anatomy of our galaxy, which Ovid in the *Metamorphoses* called "the Palatine of the Great Sky." This streak across the night sky, composed of the light from millions of distant stars, can best be viewed in the United States and Europe, the Boks note, "in the late summer on a moonless night an hour or so after sunset."

Skywatchers may also spot a shooting star. Known technically as "meteoroids," according to Robert T. Dodd in **Thunderstones and Shooting Stars: The Meaning of Meteorites** (Harvard, 1986), they continually bombard the Earth, ranging widely in size and kind from small pieces of "fluffy dust" to 100,000-ton chunks of metal.

Despite the recent leaps in knowledge about the universe and its origin, most astronomers (like most scientists) maintain that the more they learn, the more they realize they do not yet know. Hence **Revealing the Universe: Prediction and Proof in Astronomy** (MIT, 1982), edited by James Cornell and Alan P. Lightman. Thirteen scholar-essayists consider not only such matters as "the mystery of the x-ray burst sources" but also various unanswered questions now facing astronomers: Are there more than nine planets in the solar system? In what form is the universe's "hidden mass"? And could the theory of stellar evolution be wrong?

Such questions form a seemingly endless chain. In fact, physicist Werner Heisenberg observed in **Physics and Philosophy: The Revolution in Modern Science** (Harper, 1958) that "natural science does not simply describe and explain nature; it is part of the interplay between nature and ourselves; it describes nature as exposed to our method of questioning."

Astronomers utilize a specific method of questioning, one that focuses on ***how*** cosmic events occur. As to ***why*** they occur—the bigger picture—those questions fall under the rubric of "cosmology," what astronomer Edward R. Harrison calls "the science of the universe." In **Cosmology** (Cambridge, 1986), Harrison notes that cosmologists deal with such matters as the large-scale structure of the universe, its distant and receding horizons, the interplay of cosmic forces, and the nature of space and time. But, whereas "most sciences tear things apart into smaller and smaller constituents, for the purpose of examining the world in progressively greater detail . . . cosmology is the one science devoted to putting the pieces together into a 'mighty frame.'"