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.

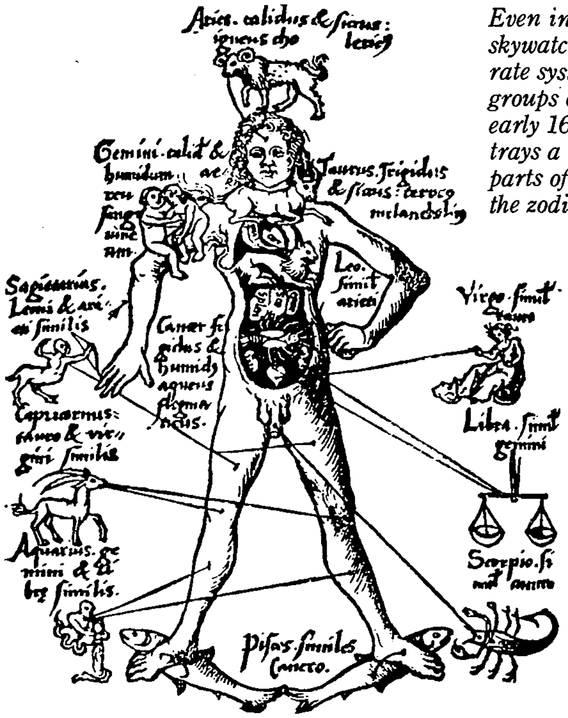
Guided by his uncle, a Roman Catholic bishop, Copernicus was elected to a position as canon (business manager) at the Cathedral of Frauenburg in his native Poland. He traveled widely, studied in Italy, and was a model scholar and churchman. From roughly 1512 on, he developed a scheme of a planetary system 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.

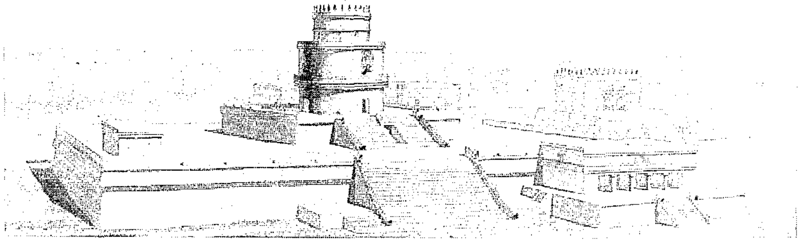
◆

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.

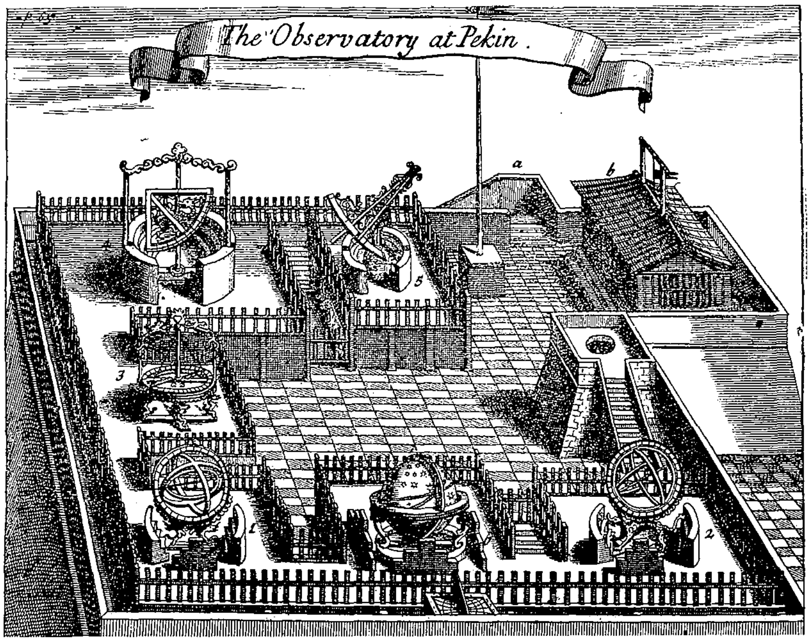
Furthermore, the maestro had a way with words, writing—unlike Copernicus and Kepler—in the vernacular, Italian in this case. Through his writings, Copernican ideas spread throughout Europe. Galileo's trial did not curb the spread of these ideas—indeed, its only effect was to guarantee that the center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

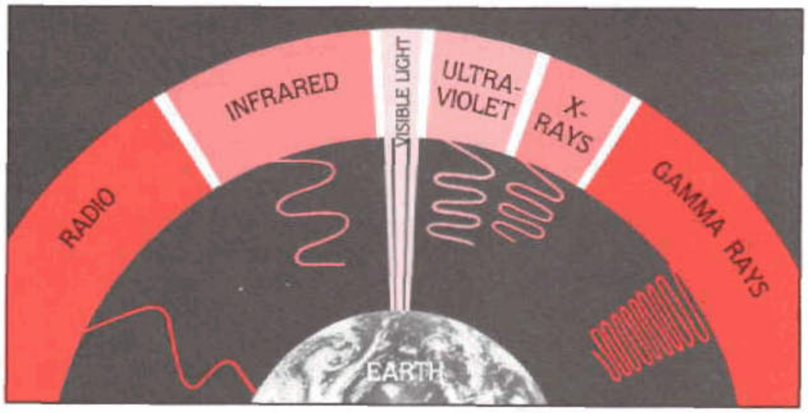
Since the discovery in 1932 that radio waves emanate from the Milky Way's center, astronomers have been scanning the "invisible" universe. That task requires special instruments. Because only visible light, radio waves, and some infrared radiation can penetrate the atmosphere, special devices are sent 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.