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.

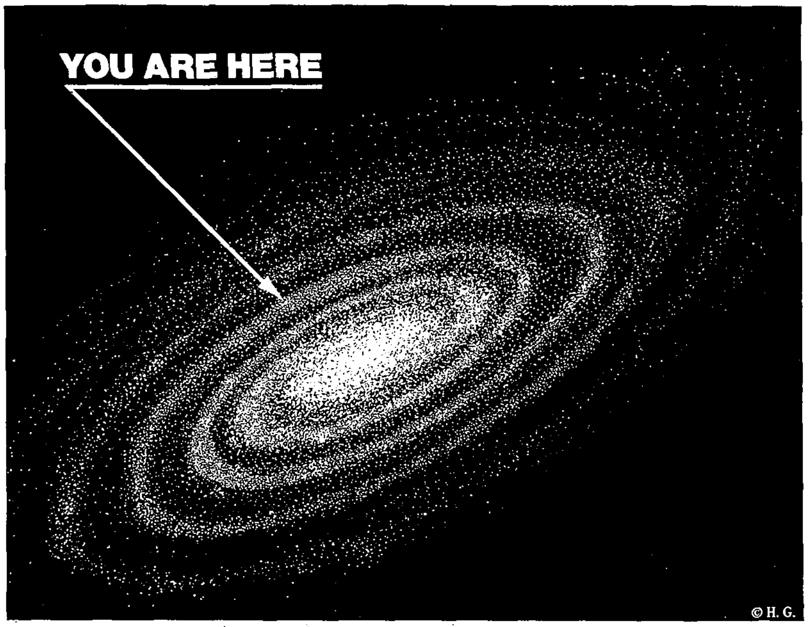
Beyond the Andromeda nebula, there are thousands of spiral galaxies like it, as well as galaxies of another kind, called elliptical galaxies. Galaxies tend to form groups of a dozen or so, and clusters of a thousand or more. The clusters are not isolated in space, but are connected by large sheets of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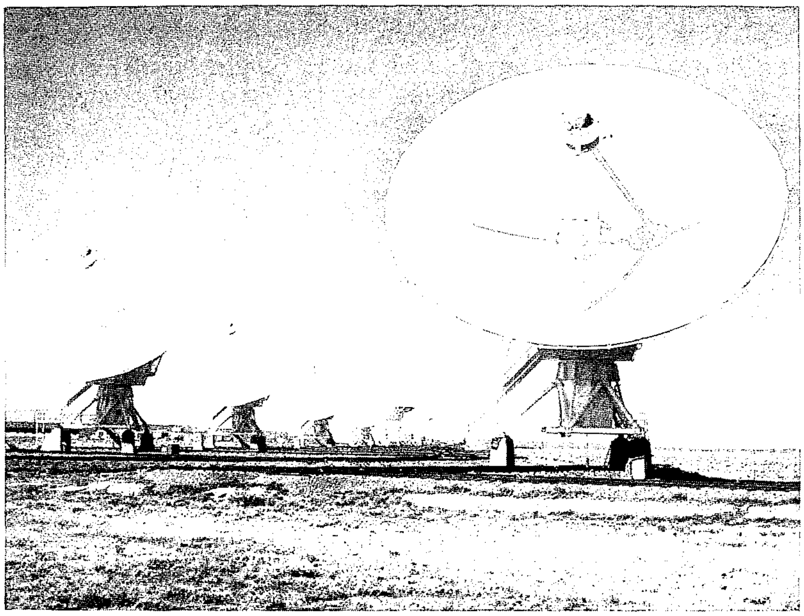


The Very Large Array, located near Socorro, New Mexico, consists of 27 25-meter reflector antennas, arranged in a Y-shaped pattern. Two arms are 13 miles long, the third is 11.8 miles long.

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.

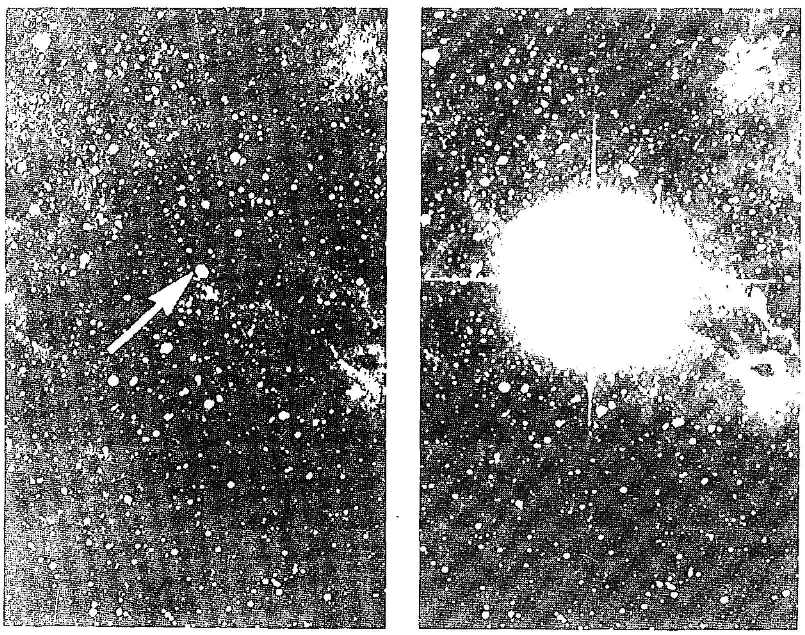
When nuclear fuel is exhausted, the core of a massive star collapses to form a neutron star weighing 1.4 times as much as the Sun; its radius is only a few kilometers. The energy released in a fraction of a second by the gravitational compression of matter is in the form of elusive particles called neutrinos. 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?