The Phenomenon of Life

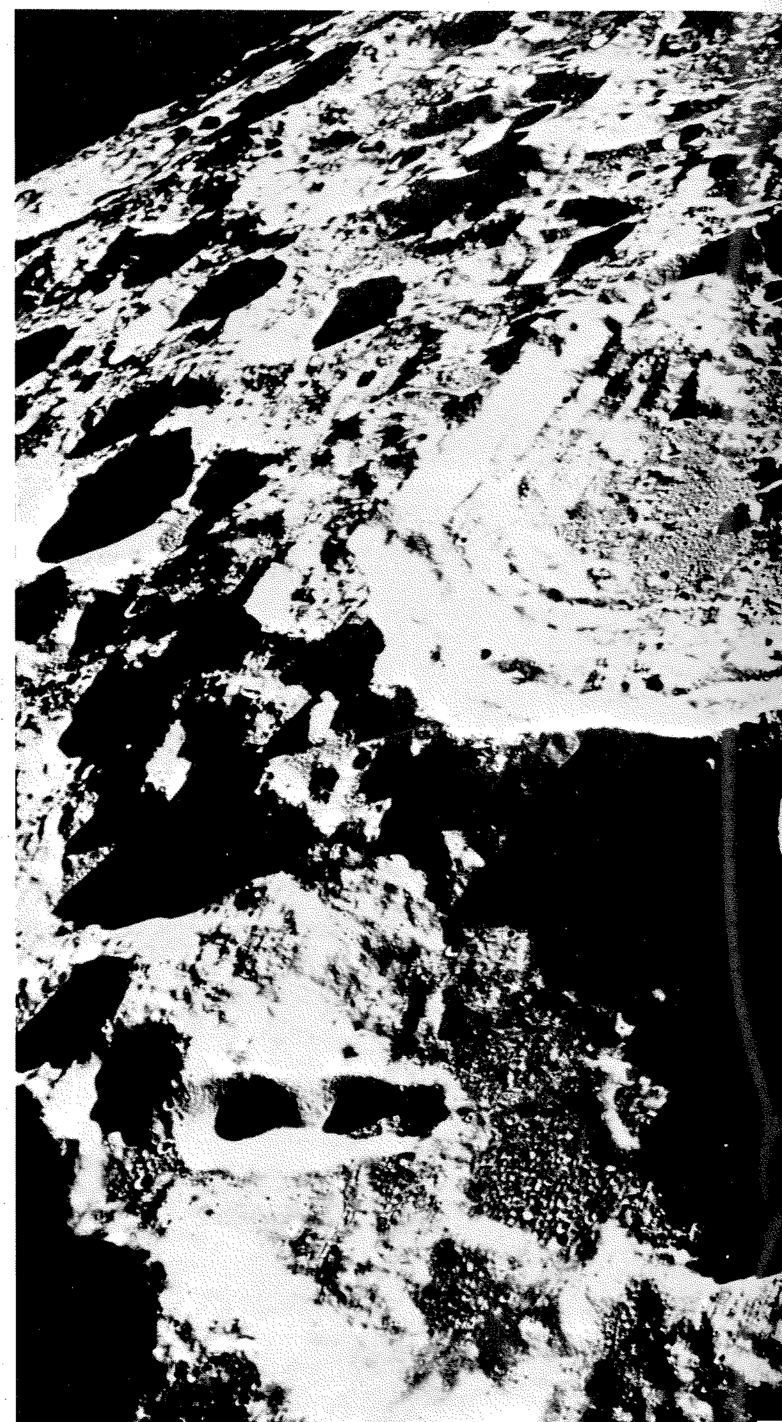
What is unique to life wherever it may be found, and what features of life are accidents of its history on this particular planet?

Very few men have ever left our planet Earth, and even fewer have seriously had to wonder whether they could get back safely. Most of us take the planet that carries us pretty much for granted. When the Catholic Church in the Middle Ages claimed dominion over "Urbis et Orbis"—City and World—it was claiming just about everything it knew of that mattered to mankind.

Kepler, Copernicus, and Galileo changed our point of view. By demonstrating that the Earth was no more the center of the universe than any of the other planets, they implied that these bodies might be worlds like ours. Fiction writers from Johannes Kepler to Jules Verne and beyond populated our neighbors around the Sun with life, humanoids, and civilizations. The astronomer Lowell built the Flagstaff Observatory in Arizona in 1894 specifically to study Mars, which he believed to be inhabited by intelligent canal-builders. H. G. Wells skirted the problem of the barren appearance of the lunar surface by postulating a subsurface civilization. Invaders from Mars and Venus became the science fiction writers' stock plot lines.

Today we are more knowledgeable and less optimistic about other life in our solar system. Mercury is a lonely cinder, keeping one face forever toward the Sun. Venus may have surface temperatures close to that of melting lead. Jupiter and the outer planets are apparently too cold. Our own Moon has been shown by the Apollo expeditions to be an airless, waterless, lifeless gray sphere, the product of four eons of meteoric bombardment and vulcanism. Only Mars offers hope, although slim, for life even of a primitive kind. More than at any time since the Middle Ages, we realize how special our own planet is.

A common theme of the Apollo astronauts has been the surprising lack of color anywhere in the visible universe save Earth. James Lovell on Apollo 8 remarked: "The Moon is essentially gray: no color. It looks like plaster of paris or sort of a grayish deep sand . . . The best way to describe this is really a vastness of black and white—absolutely no color." Charles Conrad, on Apollo 12, was even more blunt: "If I wanted to look at something that



This photograph of the far side of the Moon was taken from the Apollo 11 command module during lunar orbit. Our Moon has been shown by the Apollo expeditions to be an airless, waterless, lifeless gray sphere, the product of four eons of meteoric bombardment and vulcanism.

by Richard E. Dickerson

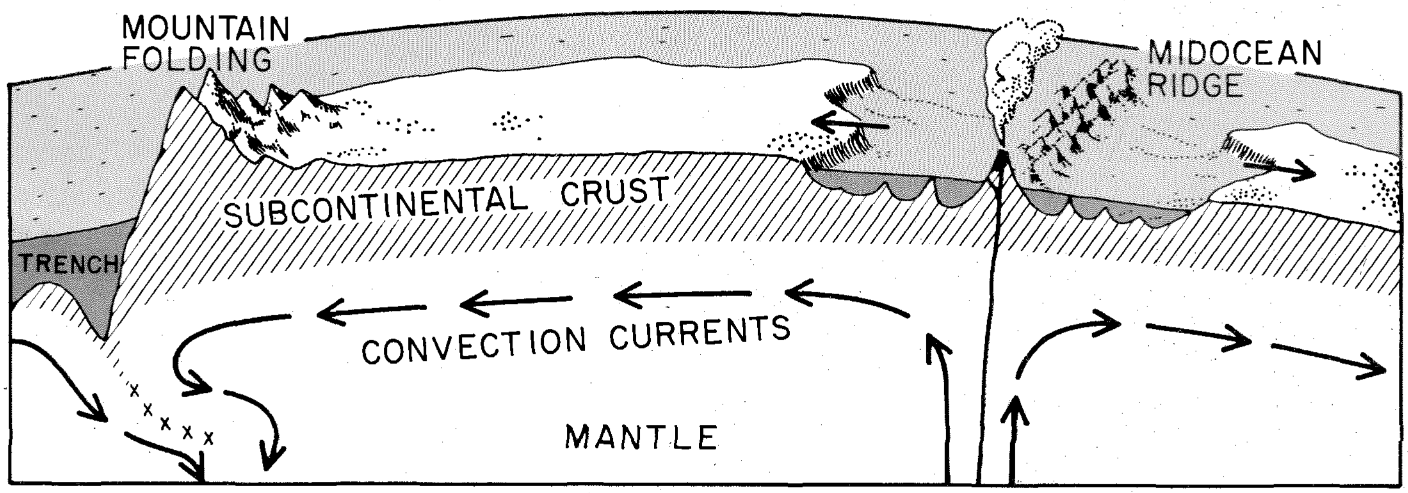
looked like the Moon, I'd go out and look at my driveway." The sky above the Moon, Conrad said, appeared to be very black, "like ebony."

The Earth presented a different picture to the first men ever to leave it completely. Lovell described it during the ascent of Apollo 8: "For colors, the waters are all a sort of a royal blue. Clouds, of course, are bright white . . . The land areas are generally brownish—sort of dark-brownish to light-brown in texture." Later, he speculated, "What I keep imagining is that, if I were some lonely traveler from another planet, whether I would think it was inhabited or not . . . I'm just curious whether I would land on the blue or the brown part of the Earth." He was moved to make what must be the most eloquent comment to come out of the space program: "The Earth from here is a grand oasis in the great vastness of space."

What makes Earth such an oasis in an otherwise inhospitable solar system? Why does Earth have seas, and why have these seas been the cradle of life? Just what is this rare and peculiar phenomenon that has appeared on the third planet alone out of nine planets? Why has the family of living organisms developed and diversified as it has on Earth, and would we expect to find similar things happening, given comparable conditions, on planets around other stars? What is unique to life wherever it may be found, and what features of life are accidents of its history on this particular planet? Some of these questions have no answers yet, some may be answered in the next decade of study and exploration, and some may never be answered until we find another planet on which this phenomenon has appeared independently. Until then, the best we can do is look carefully at what has happened in the one case for which we have direct evidence, the planet Earth.

LIFE ON EARTH

Somewhat more than 5 billion years ago, our solar system evolved, including the planet Earth. Older theories about the formation of the Earth spoke of the cooling and condensation of hot gases. Since the early 1950's, it has been considered more likely that the planets were built up by the gravitational attraction and aggregation of cold dust and particles into clumps of solid matter. As the size of the Earth grew by this cold accretion process, the weight of the outer layers compressed the center. This pressure, and energy from radioactive decay, together heated the interior until it finally melted, and the settling of heavier elements led to the fluid iron and nickel core that we have today. Around this core of radius 2,200 miles lies an 1,800-



Adapted from "Continental Drift," by J. Tuzo Wilson.

Because of its liquid core and semifluid mantle, Earth is constantly in a state of geologic change. Where currents in the mantle rise beneath an ocean, they cause spreading of the ocean floor and separation of the continents bordering it. The crust may be piled up where it meets sinking currents to produce folded mountain ranges, oceanic trenches, and deep earthquake zones. All of this has had a profound effect on the evolution of life.

mile-thick mantle made of dense silicate minerals similar to basalt. Covering this is a lighter crust, as much as 25 miles thick under the continents but only 3 miles thick under the ocean floor. This crust is the only part of our planet about which we have any direct chemical knowledge.

From the scarcity of helium and other noble gases on Earth compared with their abundance on the Sun, it would seem that Earth lost its original atmosphere. There was a time when Earth was a sterile, rocky ball with neither atmosphere nor oceans. A new atmosphere arose in time from the outgassing of the mantle and crust. Water vapor from the interior condensed into seas, which ultimately became the cradle of life.

The pattern of sea and land in those distant times was totally different from what we now find. The crust of the Earth floats on a semifluid mantle, in which convection currents of basalt flow up from the heated core, expand laterally, and sink again into the interior. One such rising current in the mantle lies beneath the mid-Atlantic ridge, with a flow to the east and west of about a centimeter per year. The Americas and Europe and Africa are slowly drifting apart, and one of the side effects of this drift has been the folding and uplift of the Rockies and Andes mountain chains. Since the beginning of the planet, the Earth's crust has been in constant motion. Sea beds have been uplifted and folded into mountain ranges, and gradually eroded down into plains which have been flooded again. The history of Earth is one of constant and ceaseless change. External accidents such as meteor impact craters have been quickly erased, and today we see only the most recent ones.

The Moon and Mars present a far different aspect. They are essentially static worlds. They have few tectonic processes comparable with continental drift and crustal folding in Earth, and we think we know why. Moon, Mars, and Earth increase in mass in a regular progression: Mars is 8.7 times the mass of the Moon, and Earth is 9.4 times the mass of Mars. Both Moon and Mars were so small that the heat generated in their interiors by gravitational pressure and radioactive decay could escape from the surface as fast as it was produced. To use a nuclear analogy, the Moon and Mars were below the critical mass for the required buildup of temperature for a molten core. If their interiors melted at all, they probably solidified again as heat was radiated from the planetary surface. They became solid balls of rock, and the convection currents that shape the surface of the Earth either never developed or never lasted. The small size and weak gravitational fields also meant an early loss of what initial atmosphere they possessed, with far less outgassing from the interior on Mars and very little at all on the Moon. One effect of the lack of molten cores in these planets is their absence of magnetic fields, verified for Mars by the Mariner project.

The oldest rock and soil samples brought back from the Moon by the Apollo 11 and 12 expeditions have been dated by uranium/lead and rubidium/strontium radio-isotope methods as 4.5 to 5 billion years old. Both expeditions found basaltic lava flows 3.4-3.6 billion years old, indicating that there was a widespread outpouring of lava over the Mare regions during a relatively narrow time interval. For the first billion years of its history, at least, the Moon was not a static ball of rock. It has been suggested that Mars, and perhaps even the Moon, might have been covered early in its history with shallow seas which were later lost as water molecules escaped the planet's weak gravitational pull and vanished into space. If so, these early moves toward an Earth-like planet were stillborn. The scars of over three billion years of history are visible on the Moon as a heavily cratered surface, and Mars also shows a surprisingly lunar-like appearance. Earth, by contrast, was large enough to develop differently.

This, then, is the stage on which life was to play out its drama—a water-covered planet, with shifting land masses in constant geological turmoil. Some time around three to three and a half billion years ago, the first actors appeared on stage. How and why chemical systems that we would describe as "living" appeared is another subject. But appear they did, and they spread throughout the seas. At one time in the history of the planet, the oceans teemed with life, including fish and well-developed aquatic plants, yet the exposed land remained as sterile as the Moon. The reason was that the land was bathed in ultraviolet radiation from the Sun—radiation so energetic as to be deadly to living organisms. Life was then confined to such depths in the seas (below 5-10 meters) as would shield out this radiation. Photosynthesis arose for another role, yet one effect of photosynthesis was the creation of an ozone layer in the upper atmosphere which blocked the ultraviolet. When this happened, the spread of life to shallow coastal waters and eventually to the land itself was only a matter of time.

Photosynthesis evolved in response to a shortage of natural high energy compounds for food. When this new method of tapping solar energy to synthesize sugars developed, life divided into two classes of organisms: those that made their own food and those that ate the food-makers—plants and animals. Both plants and animals moved onto the land in their own way: animals by migration of individuals, and plants by migration of generations, as spores and seeds were carried to new environments.

With the conquest of the land, the stage was set for the major steps in the history of life. In the animal kingdom this involved the rise of amphibia, reptiles, mammals, the special type of mammals known as primates, and finally that peculiar primate called Man. With the coming of Man, life crossed another threshold comparable to the evolution of the first life, photosynthesis, and the conquest of land. Man became the first thoroughly social animal, by virtue of his ability to communicate by speech and writing. A large part of his heritage became externalized in myths, traditions, custom, and law, rather than predominately internal and genetic. To use an only slightly exaggerated image, his genes were supplemented by libraries. The young fields of behavioral biology, anthropology, psychology, and cultural history are beyond the scope of this article. There is no clear and obvious break in the thread, however. All are stages in the history of life on this planet.

Life evolved at a time when the land and ocean distribution on the surface of the planet was quite different. The earliest traces of hominids, 5-20 million years old, come from the Olduvai Gorge in Kenya, south of the Nile delta. Man probably learned to plant grasses and domesticate animals 10,000 years ago in the Armenian and Iranian highlands north and east of Mesopotamia, and moved down into the river valleys of Mesopotamia, the Nile, and the Indus as he developed irrigation techniques. The effects of irrigation farming in Mesopotamia and the Nile valley are visible even from space as dark zones of vegetation. It puts things in their proper perspective to notice that the direct works of Man are invisible from space, and all that can be seen are his effects on the life of the planet.

CHANGE, EVOLUTION, AND INTELLIGENCE

The process of evolution is essentially conservative, and not innovative. The goal is not to bring about change, but as far as possible to counteract changes that have come about in the surroundings. To use an old example, fish did not first scrabble out of the water and across the mud flats because they wanted to open up new frontiers on land, but because they wanted to find new ponds where they could live in the old way when their former homes dried out. Reptiles did not develop hard shelled eggs to armor plate their embryonic offspring, but rather to give them an aquatic environment under conditions where the bodies of water used by amphibians were not available. To pick an earlier and more speculative example, little aggregates of chemical reactions in the primordial seas did not surround themselves with membranes in order to become more concentrated, but rather to avoid dilution. Or, recasting this in terms less offensive to the sensitive biologist, those local aggregates of chemical reactions that spontaneously synthesized membrane barriers that prevented them from being diluted and destroyed had an increased probability of remaining intact, growing, and developing.

Most evidence of external bombardment has been erased from the Earth's surface. Only the most recent impact craters are visible, such as the Barringer Meteor Crater in north central Arizona. The best calculations on impact conditions suggest that Barringer Crater was dug by an iron meteor of 63,000 tons, 81 feet in diameter, striking nearly vertically with a velocity of 9.5 miles per second. The crater is probably 40,000 to 75,000 years old.

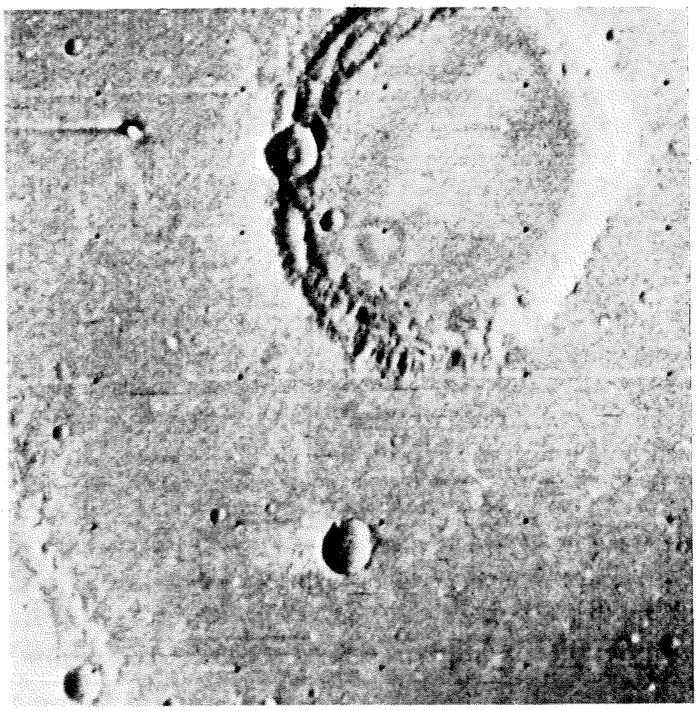
These are all examples of *homeostasis* (from the Greek *homeo-*, or "same," and *stasis*, or "state"). A well-regulated thermostat is a mechanical homeostat. It turns the furnace on, not to make the house hotter, but to keep it from cooling off when the outside temperature drops. Evolution is the history of one subterfuge after another adopted by living organisms to compensate for changes in their environment. A corollary of this is the idea that if there were no changes in the environment, there could be no evolution. This is one reason why the changeable Earth teems with countless varieties of living things, while the static Moon remains as dead as when it was formed.

Evolution is a mechanism for dealing with changes in the environment that are long in comparison with the lifetime of an individual. It can produce a strain of rabbits with unusually heavy fur as a new ice age commences over a period of many generations, but it cannot grow a heavy fur coat on an individual rabbit when unexpected cold weather comes. It can develop mammals such as whales that are adapted to the oceans that their amphibian forebears left 450 million years ago, but it cannot teach a mountain goat to swim. The great advantage of Man over the other animals is that his highly developed nervous system permits him to make rapid responses to rapid changes in his environment. Man *can* put on a fur coat or learn to swim, and can build heated houses and submarines. Intelligence is a trait which allows its possessor to adapt to changes within the lifetime of the individual. If the rabbit and whale are adapted to one set of conditions, Man is adapted to constantly changing conditions. Intelligence is a trait that one would not expect to find in a relatively static world. In a sense, we are the product of the instability of our planet.

LIFE ON OTHER WORLDS

We may find a primitive form of life on Mars, although the more we learn about Mars, especially its low water content, the less likely this appears. The reports from the Russian and American Venus probes are just confusing enough to offer continued hope. But there is a strong possibility that we are alone in our solar system.

Our Sun is a fifth magnitude star of no special character or distinction. What is the probability that another similar star would have one or more planets suitable for life? The difficulty in asking such questions is that we really do not know what to ask. How do we define the limits of conditions suitable for life, when all we have ever seen is one sample of the process? We are strongly tempted to fall into the trap of defining the conditions for *terrestrial* life, and making our boundaries too narrow. Even if we could define these limits properly, how can we estimate the probability of finding a planet with such conditions, when we have never seen a planet of another star, and only recently have been sure of detecting one indirectly by its



This Mariner 6 photograph of craters on Mars shows how closely its history may have paralleled the Moon's history. When the first shots of Mars were sent back by Mariner 4, the unexpectedly lunar appearance of the surface prompted one Caltech astronomer to exclaim, "My God, they shot the wrong planet!"

effect on the motion of the parent star? This is a fascinating guessing game, and one in which no one is likely to be able to prove you wrong.

We can draw a few boundaries, outside of which life is unlikely. To begin with, the planet almost surely must have or have had reasonable bodies of liquid present in which life could evolve. The chemistry of life is basically the chemistry of liquid solutions. Gases alone are too structureless to carry the intricate organization necessary for a system to have the properties of life, and chemical reactions in the solid state are too slow to be useful. A living organism must have solid elements for maintenance of its structural organization, and liquid in which its energy-extraction and other metabolic processes can take place. One can imagine that life, once evolved, could slowly adapt to harsher and harsher conditions as the planet lost much of its atmosphere and liquid phase, but it is difficult to imagine how or why living systems would evolve from the start in a dry and barren world. The conditions under which life could *survive* are surely harsher than those under which life would spontaneously appear.

The planet cannot be too hot or too cold. It must be above the melting point of the parent liquid, whether water or some other fluid. It must be below the boiling point of that liquid, and also below the temperature at which chemical bonds in the solid phase of living organisms are disarranged and broken. On Earth, temperatures high enough to denature proteins and destroy carbon-based organic compounds are deadly. This means that the planet must not be too near or too far from its star. Each type of star will have a "temperate belt" around it, within which planets (if present) will have suitable temperatures. The orbit of the planet must not be so eccentric as to sweep out of this temperate belt, either dangerously near the star or out on a cometary orbit into the cold.

The planet must not rotate too rapidly. If Earth were turning 15 times as fast, gravity would be nearly counteracted at the equator, and the oceans and atmosphere would be lost. With much faster rotation the planet itself would break up. On the other hand, some rotation is needed to distribute the solar heat evenly over the surface, and to set up convection currents which are necessary for mixing and change in chemical evolution. If Earth kept one face always to the Sun, as Mercury does, then the oceans and atmosphere would distill away from the sunward side and freeze on the cold and dark back hemisphere.

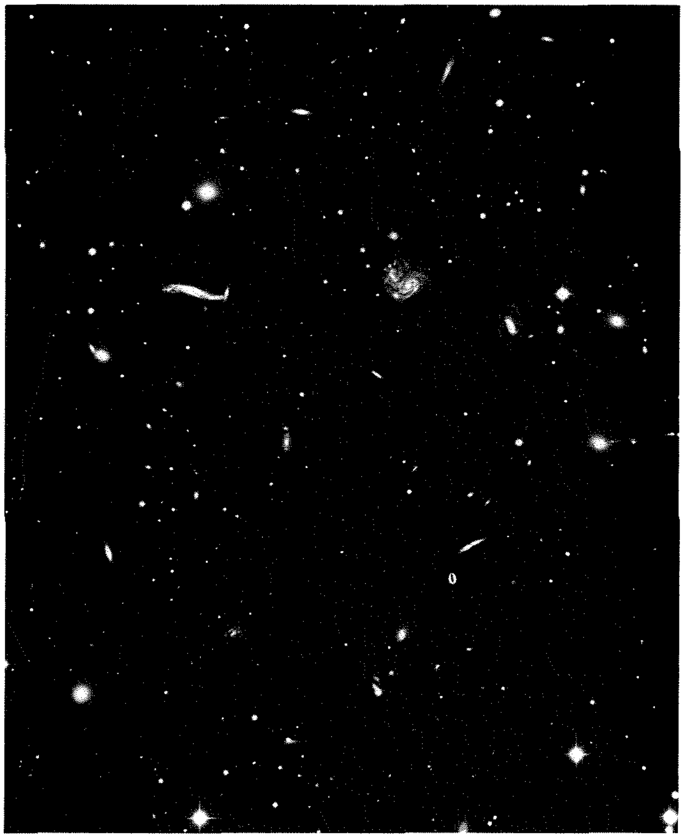
If the temperature falls below the freezing point of the parent liquid for part of the planetary year, then this liquid should be one of the relatively few that expands when it freezes. We sometimes overlook how unusual water (H_2O) is, and how advantageous its properties are to us. Imagine what our oceans would be like if ice were more dense than water, and sank to the bottom. Then the cold ocean bottom, farthest removed from solar heat, would be perpetually frozen, with static layers of water of increasing temperatures above. The summer heat might thaw the oceans down to the hundred foot level, but in winter the ice would creep up again closer to the surface. The ocean temperature would fall steadily with depth. With the heavier cold layers at the bottom, there would be no thermal convection currents such as are so typical in our real world. The oceans would be stagnant and motionless. They would be far less efficient as temperature-moderating devices, warming the continents in winter and cooling them in summer. Finally, they would be less suitable homes for evolving life. The mixing and distribution of chemical substances, and the *change* that is so necessary for chemical evolution, would not occur.

This limitation on buoyancy of the solid phase is a severe one. Other compounds similar to water, such as ammonia (NH_3), hydrogen fluoride (HF), and hydrogen sulfide (H_2S), have solids that are denser than the liquids at their freezing points. Only printers' type metal and a few other alloys of cadmium and bismuth expand upon freezing, and these are hardly likely candidates as media for life. We cannot say that water is the only liquid in which life could evolve, only that the problems created would have to be solved some other way in other liquids.

The star of a life-bearing planet cannot be a variable star, flaring up periodically to wipe out what had evolved. Judging from Earth's example, it takes something like a billion years for living systems to evolve from a chemical environment, and even longer for higher organisms to appear. The star must be stable over such time spans. The level of cosmic radiation from outside, and natural radioactivity in the planet's crust cannot be too high. Yet here we risk drawing our boundaries too close by basing them on terrestrial life. We forget how reactive and corrosive a substance oxygen gas is, and how well-designed our skin structure and body anatomy are to keep this dangerous gas channeled where it will do good and not harm. One could imagine extraterrestrial biologists eliminating Earth as an abode of life because of its corrosive and hyperreactive oxygen atmosphere. Life might evolve in a high radiation environment to produce organisms that secrete shells of lead, like some terrestrial animals do calcium.

The chemistry of life must be based on elements that can combine to build long-chain polymers of varied chemical properties. A crystal is not alive; neither is an automobile or a digital computer. As we build more advanced computers and learn more about servomechanisms and the field of cybernetics, we realize that highly organized systems can possess properties which arise less from the nature of their component parts than how they are put together. The same behavior can be brought about in systems made of quite different physical parts, providing that they are organized in equivalent ways. Computers made of electronic hardware can reproduce many of the operations of brains, made of organic materials. The key is proper organization. The machinery necessary for a system to have the flexibility of action and response that we associate with life must be intricate and complex. The structural materials out of which the system is built must be correspondingly versatile. Terrestrial life is based on the chemistry of carbon compounds, which is accordingly called "organic" chemistry. It is difficult to see what element other than carbon could serve as the basis for life. No other element has anything like the varied spectrum of compounds that carbon has, and no other element can build polymers of indefinite length. Boron and nitrogen, its neighbors in the periodic table, cannot form stable polymers of appreciable size, and only silicon, below carbon in the next row of the table, is even a vaguely likely candidate. But the *silanes* are explosively unstable, the *silicones* are discouragingly inert, and the superficial resemblance between some compounds of carbon and silicon is

What is the probability that at least one planet around a given star has the right conditions for life? According to one calculation, one out of every 200 stars should have a habitable planet. Spiral Nebula M81 in the Big Bear Constellation contains approximately one million million stars (about the same as the Milky Way Galaxy) and may contain as many as 50 million stars that could have planets comparable with Earth.



Galaxies occur in clusters, such as this one in the Constellation of Hercules about 340 million miles from our Galaxy. The spiral and lens-shaped objects are galaxies seen full-face and on edge. The brightest of them are comparable in size to our own Galaxy and the Spiral Nebula shown on the facing page. One estimate of the size of the universe predicts a total mass that would call for 10 billion such galaxies, which indicates that life may not be a unique or even a rare event.

probably misleading. Carbon dioxide gas (CO_2) in a carbonated beverage and silicon dioxide (SiO_2) in the glass that encloses it, or in pure form in rock quartz, have little in common. The chemistry of extraterrestrial life may well be radically different from that of terrestrial life, but it would probably be based on compounds of carbon with other elements.

THE PROBABILITY OF EXTRATERRESTRIAL LIFE

With all these restrictions, it may appear as if life is an unlikely occurrence. But we are really describing conditions that are likely to occur as solar systems evolve. When we believed in the older theory that the planets condensed from matter pulled from our Sun during a near-collision with another star, we had to admit that planets would be extremely rare and infrequent phenomena. But by current theories of the birth and development of stars, satellite systems are the norm and not the exception. It would be a rare Sol-type star that did not have planets. What is the probability, then, that at least one planet around a given star has the right conditions for life?

It is hard to put numbers to these ideas. Stephen Dole, in a study prepared for the RAND Corporation and published as "Habitable Planets for Man," has attempted the somewhat easier task of calculating the probability that a star has at least one planet sufficiently similar to Earth to be colonizable. He considers such factors as the prevalence of planets, inclination and eccentricity of orbit, temperature, mass, state of rotation, age, and presence of binary stars. He finds that one out of twenty Sol-type stars should have such a habitable planet, or one out of two hundred stars of all types. If his calculations have any validity, then there should be 50 habitable planets within a sphere of radius 100 light years from our Sun, and many more which, although unsuitable for Man, are perfectly capable of supporting an indigenous life.

Our Sun is one of approximately one million million stars in a spiral galaxy. Even if we assume that Dole is overoptimistic by a factor of 100, then 50 million stars in our Galaxy must have planets comparable with Earth. The galaxies occur in clusters, and one estimate of the size of the universe predicts a total mass that would call for 10 billion such galaxies. If all of these lines of thought are reasonably correct, then life is far from being a unique or even a rare event. Life is something that happens to matter when conditions are right, and they are right millions of times across a galaxy.

I have drawn a long curve through just one data point, the planet Earth. Most of this article has been speculation, but—I hope—not unintelligent speculation. It does no harm to ask questions for which there are no answers, for otherwise we would never find answers for new questions. We have a long way to go before we really understand living processes. A century ago the framework for understanding was developed in the theory of evolution, and in the following hundred years we have come gradually to realize that all life on Earth is one interrelated process.

At the present state of our knowledge, we have an incomplete picture of only one example of a general phenomenon. We shall know more eventually; and one of the readers of this article may be the first to detect extraterrestrial life in some future planetary probe, or make some breakthrough in understanding terrestrial life. The Romans named the first month of the year after Janus, a god with two faces who could look backward in time as well as forward. Man is the first animal to have the ability to look backward, in the sense that he can study and contemplate the process of evolution that produced him, as well as participate in it. We have the ability to decide, consciously, what will happen next in the history of life on this planet. It is a grave responsibility. As one biologist once remarked, it is not at all certain that superior intelligence confers a long-term survival advantage on the species that possesses it. But we may increase the probability of making the right decisions if we realize that we are not a lone and lonely addition to the world, but are in fact a natural outgrowth of the phenomenon of life.