COSMIC EVOLUTION: A SYNTHESIS OF MATTER AND LIFE

by Eric J. Chaisson

Since the dawn of civilization men and women have wondered about and even feared the mysteries of the skies. At first they approached their world subjectively, believing Earth to be the stable hub of the universe, with sun, moon, and stars revolving about it. Stability led to a feeling of security or at least contentment—a belief that the origin and destiny of the cosmos were governed by the supernatural.

With the advent of recorded history, however, human beings became aware of another mystery—themselves. Indeed the origin and the destiny of man are as enigmatic as anything in the depths of space.

Later, but only as recently as a few hundred years ago, man began to adopt a more critical stance toward himself and his universe, seeking to view the world objectively. With it modern science was born, the first product of which was the Copernican crisis. The idea of the centrality of Earth was demolished forever. Human beings came to feel that they were marooned on a tiny particle of dust drifting aimlessly through a hostile universe. This loss nevertheless was coupled with the emergence of the scientific method, in which observations generate a hypothesis to be followed by experimental testing, providing a new way of probing the most fundamental questions of our origin, our nature, and our future.

Recent scientific developments, particularly within the past two decades, have demonstrated that as living creatures we inhabit no very special place in the universe at all. We live on what appears to be no more than an ordinary rock called Earth, circulating about an ordinary star called the sun, at the edge of one galaxy called the Milky Way, one galaxy among countless billions of others distributed throughout the observable abyss called the universe.

It is perhaps a sobering thought to recognize that we play no special role in the universe, either astrophysically or biochemically. It is even

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more humbling at first—but then wonderfully enlightening—to recognize that it is gradual cosmic evolutionary processes, operating over almost incomprehensible time and incomprehensible space, that have given birth to life on our planet. And should the scenario of cosmic evolution be valid, even in its broadest perspective, we can speculate rightfully about the associated implication for the plurality of extraterrestrial life throughout an almost inconceivably vast universe.

As we enter the last quarter of the twentieth century, experimental science is beginning to unravel the subtleties of cosmic evolution whereby we have come first to exist and then to contemplate our existence within the material universe. With a large degree of assurance we now understand better the astrophysical sequences whereby countless billions of suns were born and died to create the matter that now composes our world. And, though substantial gaps remain, modern experimental science currently strives to demonstrate a clear understanding of the biochemical pathways that led to life as a natural consequence of the evolution of matter.

To answer the fundamental questions "Who are we?" and "How did we come to be?" it is necessary to look far into the past, beyond the commencement of the scientific method centuries ago, beyond the onset of language and civilization as we know it tens of thousands of years ago, beyond the ancestral *Australopithecus* man-ape that roamed the savannah in search of meat several millions of years ago, even beyond the multicellular organisms that began to flourish on our planet some billion years ago. Back and back your thoughts spin through the biological record—facts of evolution documented by the fossils, a record that clearly shows complexity arising from simplicity.

Go back further into the past. There was a time about four thousand million (or four billion) years ago when, according to the fossil record, there apparently was no life on planet Earth. A combination of astronomical and geological considerations furthermore suggest that the sun and planets did not even exist some five billion years ago. They were only forming out of a giant, swirling interstellar gas cloud at one edge of an enormous complex of older stars that already had been around in one form or another for about five billion years.

Here, in this so-called Milky Way Galaxy, massive stars ejected, through supernova explosions, their synthesized elements into the surrounding galactic or interstellar medium. Out of this debris other, later-generation stars condensed—at least one, our sun—with rocky planets. And it was in a billion-year-old ocean and atmosphere of primordial Earth that some critical elements combined, according to the laws of physics and chemistry, to form the biochemical precursors of life as we know it. Rudimentary life eventually arose as a selfassembly of macromolecules, and it is from such simple unicellular organisms that all more advanced, multicellular, even intelligent forms of life have arisen.

Who are we? Where did we come from? In essence we are a combination of chemical elements, produced eons ago inside the fiery cores of massive stars, elements that contribute to the earth's rocky continents, to the atmosphere and ocean, and to the myriad forms of life around us. The proper answers to these questions are evolutionary ones that enable us to relate ourselves to all forms of matter, indeed to the whole material universe.

To trace the specific steps that led to our origin, modern science attempts to synthesize a wide variety of university offerings—physics, chemistry, astronomy, biology, geology, and anthropology, among others—in an attempt to unravel the two most outstanding problems of our time: the origin of matter and the origin of life. If we can understand better the scenario of cosmic evolution, then perhaps we can determine precisely who we are, specifically how it is that life originated on this planet, or, incredibly enough, how it is that living organisms have evolved large enough neural processes to invade land, to generate language, to create culture, to devise science, to explore space, or even to be able to speculate about ourselves as you and I are doing by reading and writing this article. (See fig. 1.)

Yet there was a time when none of these capabilities existed on this planet. Long ago there was no life on Earth. There was no Earth, no sun. Somehow the heavy elements synthesized, the solar system formed, and thereafter life originated, all apparently as a general development of universal matter.

There is, among many smaller ones, at least one great evolutionary link in our ancestral past—a link which connects coagulations of matter that are clearly living with those that clearly are not.

UNIVERSE

The central theme of cosmic evolution is that, given sufficient amounts of time, life arises as a natural consequence of the evolution of matter. Then one reasonably can ask: Whence did matter arise? To address this fundamental inquiry we must consider events at the earliest epochs of the universe.

Contemporary cosmology holds that the universe began in a cataclysmic explosion some fifteen or twenty billion years ago. Evidence for the initial fireball, or "big bang," comes primarily from observations of external galaxies out beyond our Milky Way. Kinematic studies of such objects show them to be receding from us at a rate proportional to their

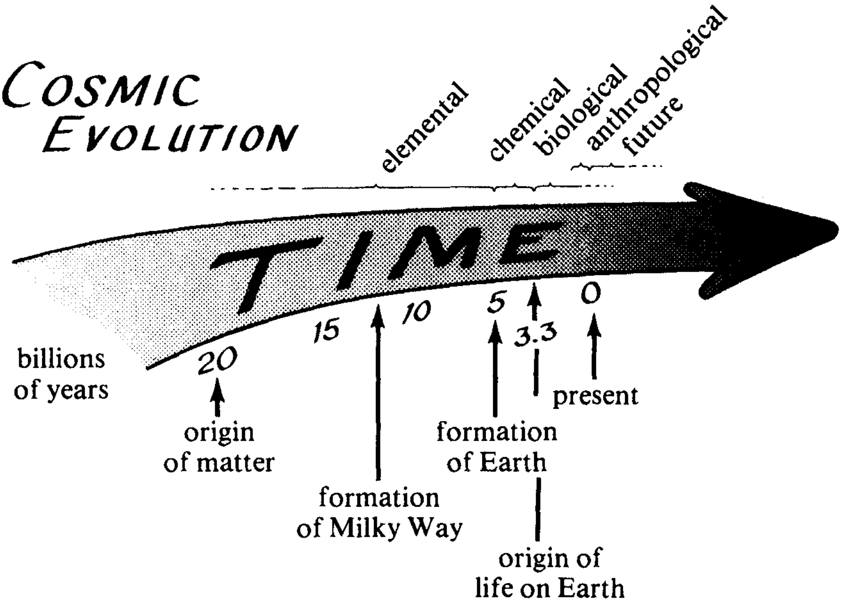

Fig. 1.—A schematic diagram of the cosmic evolutionary scenario

distance. That is, those galaxies most distant from us have larger recessional velocities, some with a fair fraction of the speed of light. Now, because of the finite speed with which light (or any type of radiation) travels, the most distant objects are also the oldest, having emitted their light toward us eons ago at the earliest epochs of the universe. This is why the cosmologist often notes that looking out into space is equivalent to looking back in time. The most distant galaxies have the greatest velocities of expansion since they were formed when the universe was young and energetic and hence provide for us information about the early universe.

The big-bang model for the origin of the universe has received supporting evidence within the past decade with the discovery of a weak hiss of radio radiation. This low-level static, observed coming from every direction of space, is regarded as a cool relic of the initial fireball. Extrapolated back in time, it also provides information about universal physical conditions eons ago.

At the very beginning the temperature of the fireball was unimaginably hot. But as the universe expanded to fill a larger volume, it began to cool, just as any gas will cool upon placement in a larger container. It can be shown mathematically that after about fifteen or twenty billion years of expansion the remnant of the initial fireball should have cooled substantially to the value now measured isotropically (in all directions) by large radio telescopes.

An important consideration for our cosmic-evolutionary scenario is the observed fact that the universe is not static. It is changing with time; it is evolving. But what is our position in this expanding universe? If all galaxies appear to be receding from us, are we at the center of the universe? No. Relativity theory specifies how the gravitational fields of massive bodies alter the nature of space and time and, along with the Cosmological Principle, ensures that all observers in space see the universe in essentially the same way. The observational fact that virtually all galaxies retreat from us is not an indication of any special place in the cosmos; the four dimensions of space and time are warped so that all observers, everywhere, would note the galaxies receding.

Present knowledge of physics does not allow us to appreciate fully the extreme conditions that must have existed in the first few moments of the initial fireball. Surely there were elementary particles out of which present matter is composed. But the extreme heat of the early universe ensured that radiation completely overwhelmed matter, breaking it apart as soon as it formed, preventing even the simplest elementary particles from coagulating into matter that we now call atoms. Eventually however—probably after only the first few minutes and certainly not longer than a million years after the initial fireball—the radiation dispersed sufficiently into a larger volume, cooling as the universe expanded. Elementary particles of electrons and protons then united to form the simplest and most abundant element, hydrogen. And yet, before the first few seconds had elapsed and the universe had had a chance to cool below ten million degrees Celsius, some of the hydrogen atoms would have had time to fuse, via thermonuclear processes, into the next heaviest element, helium. But the few seconds of intense heat available after the explosion was not time enough to permit the formation of elements heavier than helium. The elements composing the page you are now reading or the air you are now breathing were not synthesized in the big bang. There simply was not enough time; events at the start of the universe happened very rapidly.

GALAXIES

A million years or so after the bang, the universe had cooled sufficiently for matter to dominate radiation. Though probably distributed uniformly at first, matter, if left alone, tends to coagulate inhomogeneously. This is because a uniform, unbounded, self-gravitating medium is basically unstable and eventually will fragment into individual pockets of matter. Some of these statistical fluctuations will disperse, but others will grow, especially in the presence of turbulence that was surely there in the early universe. Those material fluctuations (or eddies) that continue to grow by gravitationally attracting additional matter ultimately fabricate the galaxies. Provided there is enough mass—at least one hundred billion times the mass of our sun—a reasonably warm condensation will contract gravitationally, rotate a little, heat up, radiate energy, contract some more, rotate a little faster, and so on in this cyclical fashion until an equilibrium is achieved between the inward pull of gravity and the outward force of rotation.

In this way it is thought that all galaxies were formed in the first few billion years after the bang. Observationally there indeed appear to be no young galaxies. There is no evidence for galaxies forming at the present epoch. Of course stars are still forming within galaxies, but galaxies themselves are not. Evidently the present disposition of the universe is not very conducive to the formation of galaxies. Perhaps the large-scale turbulence, the hotter gas, and the intense radiation field of the early fireball—physical conditions that have diminished substantially in the present quiescent universe—played efficient roles in sweeping up all the available matter into primordial coagulations that eventually became the galaxies now observable in deep space.

STARS

Fragmentation of matter continues even at the present epoch, producing stars within galaxies. Pockets of gas form, almost by accident, via statistical fluctuation, much as for galaxies noted above. But galactic or interstellar gas is very cold, generally only a few degrees above absolute zero, resulting in considerably less mass per pocket than for galaxies. One might ask then: How many hydrogen atoms are necessary for the collective pull of gravity to prohibit a pocket of gas, once formed, from dispersing back into the interstellar medium? A hundred? A thousand? A million? No, a much larger number. In fact nearly a billion trillion trillion trillion trillion atoms are necessary to bind gravitationally a gaseous condensation. In scientific notation this is 10^{57} (which is equal to one followed by fifty-seven zeroes) atoms of hydrogen, which, not coincidentally, is the equivalent mass of our sun. It is a large number, larger than the 10^{25} grains of sand in all the beaches of the world, even larger than the 10^{51} protons and neutrons in all the earth's nuclei. It is large compared to anything with which we are familiar because there is simply nothing on Earth comparable to a star.

Most stars in our galaxy (and, as best we can tell, in other galaxies as well) have between 10^{56} and 10^{60} hydrogen atoms, or equivalently a mass between 0.1 and 1,000 times the mass of our sun. The most massive stars probably form either in particularly rich locations of the interstellar medium or in regions where heat, rotation, and/or magnetism competed with gravity, requiring the protostellar condensation to attract more than the canonical 10^{57} hydrogen atoms for the onset of gravitational contraction.

As an interstellar cloud undergoes collapse, the microscopic spaces among the individual gas particles diminish, increasing the frequency of atomic collisions. Collisions imply friction, and of course friction is heat. Consequently the interstellar cloud heats up until such time that the cloud, or a small dense portion of it, reaches ten million degrees Celsius, at which point nuclear burning is initiated. This is a fusion process whereby individual hydrogen nuclei—namely, protons—have so much energy and therefore are moving so fast that their mutual collisions can interpenetrate the domain of the nuclear forces, fusing the protons into a helium nucleus. This so-called proton-proton cycle is the relatively simple mechanism that provides the uniform rate of stellar energy to sustain life on our planet. It, or some process like it requiring equally high temperatures, is understood to give rise to nuclear fires in the cores of all other stars, including all those seen above on a clear night.

Until recently this cloud-collapse scenario was little more than just that—a good theory but one for which there was very little observational evidence. Technological advances in the last few years, however, have enabled radio astronomers to probe deep within the dense, cool regions thought conducive to star formation. Such protostellar regions are often dark and dusty, effectively prohibiting useful work by conventional optical techniques. Light radiation, with a wavelength comparable to the typical size of an interstellar dust particle, is scattered and attenuated badly in relatively dense and dusty regions. Radio waves have a longer wavelength and are completely unaffected by interstellar debris, allowing the radio astronomer to listen to the physical processes deep within protostellar regions. Recent radio studies of candidate regions have produced some observational evidence that individual interstellar clouds indeed are collapsing under the force of gravity, presumably on their way toward formation of an individual star or cluster of stars.

The lifetime of a star, once formed, depends on its mass. Our sun is considered an intermediate-mass star and has been fusing hydrogen into helium for almost five billion years. And, according to our knowledge of stellar evolution, the sun should continue to do so for another five billion years, continuing to provide that constant source of heat and light necessary for the maintenance of future generations of Earth life. As the sun grows old, however, its helium content undoubtedly will increase, especially in the core. Though the sun's interior is amply hot to continue to fuse hydrogen into helium, it is not quite hot enough to fuse helium into the heavier elements. Lacking a nuclear fire, the sun's core subsequently will cool and, without outward radiation pressure to support gravity, shrink. The core shrinkage continues for about a billion years until the density at the core is sufficiently large for collisions to increase the temperature and hence the outward pressure, eventually matching the inward pull of gravity and thereby stabilizing the core once again. The core temperature is now high enough (about one hundred million degrees Celsius) for helium nuclei to penetrate the range of nuclear forces upon collision and, in doing so, to produce the heavier element carbon.

Simultaneous to these core events, the solar periphery is heated by the underlying helium core to temperatures well in excess of the ten million degrees Celsius needed to fuse hydrogen into helium. The proton-proton cycle consequently speeds up, producing greater amounts of nuclear energy and overwhelming the inward pull of gravity in the sun's outer layers. So, despite the helium core shrinkage to a size not much bigger than the earth, the outer solar layers expand enormously, engulfing the interior planets Mercury, Venus, and perhaps Earth. In this way our sun someday will become a red giant star. Fortunately it will not happen for another five billion years.

All stars are thought to obey the above evolutionary scenario, but their future depends critically upon the amount of mass they contain. A star having the mass of our sun or a little less will never achieve a large enough pull of gravity to squash the carbon core of a red giant to the six hundred million degrees Celsius required to fuse two carbon nuclei together. Without a carbon nuclear fire in a red giant, gravity will overwhelm the gas pressure rapidly, shrinking the entire star to one of Earth dimensions—a white dwarf. Such a star, which is white hot simply because of stored heat, eventually will fade into death as a black dwarf. Astronomers are unsure how many of these dark clinkers exist in space, for they cannot be seen.

Stars more massive than the sun, on the other hand, can achieve enormously high temperatures in their cores, temperatures capable of producing many of the heavier elements familiar to us. A series of successive core shrinkings, followed by heating and renewed nuclear burning, routinely produces many heavy elements, such as oxygen, magnesium, silicon, and sulfur, up to and including iron. But iron acts as a fire extinguisher, absorbing energy upon fusion and robbing the nuclear fire of the higher temperatures necessary to balance the relentless pull of gravity. The star consequently collapses until nuclei touch one another, halts momentarily, and then suddenly rebounds in a supernova explosion, ejecting its heavy elements and about half of its original mass into the surrounding interstellar medium.

Provided the unexpelled stellar core exceeds several solar masses, it may proceed toward any of several bizarre states, possibly even collapsing catastrophically to form a black hole. Such remnants of supernova explosions, recently observed indirectly by instrumented spacecraft orbiting the earth, are regarded as sites of extraordinarily large density, where the nature of space and time becomes radically altered and where perhaps even the laws of physics, as we know them, break down.

The temperature achieved at the moment of explosion is sufficiently high to synthesize many elements heavier than iron. Elements such as nickel, tin, bismuth, gold, uranium, and many others are produced by a series of complex nuclear reactions, precise knowledge of which has been acquired only in the past two decades during controlled experiments conducted in sophisticated nuclear plants built by our civilization on Earth.

The theoretically computed abundance of all the elements processed in stars agrees well with the observed relative abundances of all the 105 natural and radioactive elements presently known. However, it is impossible to prove conclusively that we understand precisely all the steps of elemental nucleosynthesis. It is simply impossible to probe the chemical constitution of a star's interior. But observational studies of stellar age, surface composition, and physical disposition, coupled with a solid experimental knowledge of nuclear physics, have confirmed our belief in the general scheme of stellar nucleosynthesis. In fact we know that at least one such nuclear process actually does occur within stars because of the observation of the rather special heavy element, technetium. Since this element has a radioactive half-life of only two hundred thousand years, the widespread observation of this element in numerous stars demonstrates the validity of the stellar nucleosynthetic process sketched above.

The upshot is that the interstellar medium is enriched regularly by exploding stars, which eject heavy elements for later-generation stars, planets, and other things, including living organisms, that consist of heavy elements. Because observations show that our sun already contains minute amounts of heavy elements, despite its relative youth and cool interior, we regard our sun as a second- or later-generation star. It, along with the planets, presumably condensed about five billion years ago from a cool cloud of interstellar matter already enriched with heavy elements.

PLANETS

Astrophysicists can agree on this broad outline of the origin of stars but can come to no consensus concerning the specific details of the birth of our solar system. The real problem is that the earth's geological record for the first half-billion years or so is missing, eroded away by violent internal (volcanic) and external (meteoritic) events that completely altered the makeup of the early surface.

The genesis of a planetary system is understood to be the outgrowth of a frequent, natural phenomenon that develops as a by-product of star formation from the gravitational contraction of an interstellar cloud. A huge disk of interstellar gas and dust, flattened by rotation, breaks up into eddies—or protoplanets—of irregular size and shape, moving at various distances from the protosun's center. Given the remarkably ordered architecture of the entire solar system, including Earth, it does not seem reasonable that the planets could have materialized by some collisional encounter or other chance arrangement.

The so-called nebular hypothesis of planetary-system formation then clearly implies the plurality of planets in circulation about other stars. Thus far, however, astronomers are unaware of the unambiguous existence of any other planetary system. To be sure, there are a few nearby stars that are observed to wobble back and forth slightly on the plane of the sky—as might be expected if reasonably massive but unseen companions were orbiting about them. But no Earthlike planets around other stars have ever been observed with telescopes.

LIFE

What was it like on the surface of primordial Earth? With the exception of helium (which is inert and hence plays no role chemically), the most abundant elements must have been hydrogen, carbon, nitrogen, and oxygen. Many of these light gases that composed Earth's primordial atmosphere probably soon escaped into space because of a combination of astronomical and geological events that produced a surface considerably hotter than at present. But continued volcanic outgassing from the interior of the active planet surely produced a secondary atmosphere rich in hydrogen, though probably depleted in free oxygen. Many elements are known to unite spontaneously under such nonoxydizing conditions and, especially as the earth cooled, to produce chemical molecules such as ammonia (a mixture of hydrogen and nitrogen), methane (a blend of hydrogen and carbon), and water (a hydrogen-oxygen coalescence). Observations of these very substances in the atmospheres of the larger planets Jupiter and Saturn, as well as in the dark, dense clouds of the interstellar medium, provide strong evidence that such compounds indeed must have existed at an earlier epoch in Earth's history.

In the absence of free oxygen there of course would have been no appreciable ozone layer. Lack of ozone allowed solar ultraviolet radiation to interact unabated with the imperceptibly small but relatively abundant chemical compounds. Remarkably enough, laboratory experiments now have shown conclusively that the application of radiant energy causes such simple chemicals to synthesize moderately complex products. After about a week of energetic irradiation of ammonia, methane, and water, a variety of amino acids and nucleotides is formed. These prebiological materials constitute many of the necessary molecular ingredients for life as we know it, the very building blocks of proteins and nucleic acids common to all life, from amoeba to man.

Recent biochemical experiments furthermore have shown that any of a wide variety of energy sources can suffice for the production of these precursors of life; not only solar ultraviolet radiation but also lightning discharges, volcanic heat, natural radioactivity, and atmospheric shock waves produced by incoming meteorites are all individually capable of synthesizing copious amounts of amino acids and other antecedents of the even more complex ingredients necessary for life.

Admittedly there is a large gap between amino acids—even complex proteins—and life itself. But in recent years laboratory simulations of the primordial ocean and atmosphere have demonstrated the existence of chemical compounds of substantial complexity. Polymerization experiments, in which numerous amino acids are united under the sole influence of slight amounts of constant energy, have fashioned proteinoid sequences that behave to some degree like the contemporary biological cell. Such protein or near-protein material resists dissolution in water and tends to coagulate into small droplets, sometimes called microspheres, much like oil globules floating on the surface of water. These laboratory-synthesized droplets are reasonably stable and possess a semipermeable membrane capable of directing inward the passage of small molecules used in the catalytic activation of more complex molecules too large to pass back out through the membrane. In this way proteinoid droplets, synthesized from the initial conditions that must have existed on primordial Earth, can be considered to possess a mechanism of food gathering—a primitive metabolism. They consequently grow, taking in nourishment from the surrounding primordial soup where organic matter is still produced via interaction with a source of external energy. Ultimately the normal operation of the laws of fluid physics governing weight, size, and surface tension tends to break up the larger droplets into smaller ones, some of which dissipate, others of which survive.

Can these proteinoid substances be considered alive? It is hard to say. It is difficult to define life. Some biochemists regard such curious little bags of chemicals as possessing many of the characteristics of a living unicellular organism—they eat, eject wastes, exhibit metabolic processes, grow, reproduce, and die. They possess, however, neither the hereditary molecule DNA nor a well-defined nucleus. To be sure, laboratory biochemists have not yet succeeded in synthesizing from primitive Earth conditions the DNA molecule or many of the exceedingly complex enzymatic proteins common to contemporary life. Neither can they justify how the first protein arose from a medium containing no nucleic acids, especially when the passage of information from nucleic acid to protein is considered by many to be the central dogma of contemporary molecular biology. But if the aforementioned synthesized droplets are not at least progenitors of living organisms, then nature would appear to have played an unusually malicious joke on modern science.

The basic problem here is that there is no clear-cut distinction between living and nonliving. Most scientists would argue that the amoeba is alive but that the dilute organic soup in the laboratory simulations or on the primordial Earth is not. The proteinoid droplets appear to be somewhere in between. However, they do bear a certain resemblance to the fossilized remains of the oldest living organisms found several years ago in the sedimentary rocks of South Africa. These fossils, radioactively dated at 3.3 billion years old, appear to have a microbiological morphology not unlike that of modern blue-green algae.

A central feature of cosmic evolution then is the developing realization that life is a logical consequence of known physical and chemical principles operating within the atomic and molecular realm and, furthermore and more fundamentally, that the origin of life is a natural consequence of the evolution of that matter.

With the passage of almost inconceivably long durations, Earth's geophysical environment changed sporadically, granting some biological species a natural advantage over others, thereby giving rise to a myriad of living organisms. Biological evolution by natural selection is considered now to be a paleontologically documented fact. The key is the fossil record.

Briefly the study of fossil remains shows the widespread appearance about 2.5 billion years ago of simple unicellular organisms, such as blue-green algae—procaryotic systems lacking a well-defined nucleus.

These were followed about two billion years ago by more complex unicellular creatures—eucaryotes having well-defined nuclei, such as the euglena. Multicellular organisms such as sponges did not actually appear until about one billion years ago, after which there rapidly flourished a wide variety of increasingly complex organisms—insects, reptiles, mammals, man.

But the fossil record also contains abundant evidence that some organic species did not adapt successfully to the changing environment and subsequently perished. In fact despite the present existence of some two million living species, biologists estimate that more than 99 percent of all species of organisms that have ever lived on Earth are now extinct.

The fossil record no longer leaves any reasonable doubt that biological evolution by natural selection has occurred and is continuing. The precise mechanisms of evolution, however, are debated still in some circles. Contemporary thought stipulates that chance mutations sporadically produce genetic variability in the DNA structure, acting as the motor of evolution and enabling organisms to strive for the best available niche. For example, some early mutations apparently allowed primitive protocells to use light energy, exclusively and without molecular nourishment, to sustain themselves via the process we now call photosynthesis. The 3.3-billion-year-old fossils show some evidence of chlorophyll products, implying a widespread occurrence at that time of photosynthesis, a process whereby carbon dioxide is converted to oxygen, which we now breathe, and the carbon and water to carbohydrates which the cell assimilates.

At any rate it is fair to say that twentieth-century evolutionary theory is quite capable of accounting for the wide variety of life on Earth, of explaining variations of species from ideal types, and of recognizing that universal change occurs everywhere in nature as a rule and not as an exception.

INTELLIGENCE

Life thus began on our planet at least 3.3 billion years ago. For about 2.5 billion years evolution did not take matter beyond the single-cell way of life. Macroscopic evolutionary developments occurred only within the past five hundred million years or less, with animals themselves mastering the land only about three hundred million years ago and birds, mammals, and flowers flourishing less than two hundred million years ago. Interestingly, manlike creatures have been around for only the last few million years, and our own species less than a tenth of a million years—an exceedingly short time when placed in perspective within the entire cosmic-evolutionary scenario. In fact if all events from the origin of life to the present could be compressed into a twenty-four-hour day we would have existed for less than a minute—a short time indeed in the cosmic scheme of things but apparently not short enough for us to avoid ransacking our planet of fossil fuels and natural resources.

The precise lines of descent whereby the ape-man evolved from the man-ape remain debatable. The general picture is in place, however. Paleoanthropologists seek to trace our recent origin by unearthing fossil remnants of our ancestors in rich river beds, principally along the East African Rift Valley. Here in recent years substantial skull, jaw, and tooth fragments have been discovered, providing a wealth of information regarding our immediate predecessors. But molecular biologists argue that one cannot tell a damn from a bone, despite an apparent agreement among all researchers that in principle fossils someday will be numerous enough to delineate unambiguously the true course of recent evolution. These behavioral scientists argue that the underlying reasons for evolution can be revealed only through the study of our closest living primate relative—the ape, particularly the chimpanzee.

At any rate the consensus has it that genetic variability within a changing environment rapidly caused ratlike, insect-eating, tree-dwelling creatures of about seventy-five million years ago to transform paws into hands for gripping and leaping, to convert smaller bodies into larger ones for greater protection, and to trade the sense of smell for a keenness of vision. The fossil record of about forty million years ago shows that the prosimians with longer arms, dexterous hands, and binocular vision simply had a natural advantage in gathering food at the end of a branch and thereby had an increased opportunity for survival.

Even today studies of the behavioral patterns of chimps demonstrate clearly their uncanny ability to strip leaves from a twig, insert the twig into a termite mound, and systematically lick off the termites. Conduct of this type clearly requires not only adept manipulation but also substantial intelligence. An increased dependence on the hands clearly has an evolutionary effect on the brain—it gets bigger.

Well, does this conceivably lead to the evolution, via continued genetic alteration, of an erect, large-brained, sophisticated, culture-oriented chimp? Theoretically, yes, if we wish to call the erect descendants of the prechimp a chimp. But we do not; instead we call the erect one that came down to the ground *Australopithecus* and the one that stayed up in the trees eating figs a chimp. Why did one kind come down to the ground? We do not know for sure. Perhaps one type of chimp hogged the figs, unwittingly encouraging the development of a ground-dwelling survivor that eventually has come, as man, to dominate the chimp and all other life on the planet.

Actually, recent fossil findings supported by radioactive studies suggest that there coexisted two distinct species of *Australopithecus* a few million years ago, a genus thought by many to represent the missing link between man and ape. Bone fragments attributed to *Australopithecus,* displaying a mixture of apelike and manlike characteristics, come in two sizes: a gracile, slender-jawed species with small molars and a robust, heavy-jawed species with extremely large molars conducive to the eating of coarse vegetation. But the fossil record shows dramatically that there are no *robustus* findings more recent than a million years ago, clearly implying that *gracile,* our immediate ancestor, expanded his brain, his capabilities, his niche, and hence crowded *robustus* right off the face of the earth.

Homo thus emerged as a new genus of the animal kingdom. The dominant genus. But what makes man unique? The brain? No, not really. Even such primitive creatures as the paramecium and the half-inch-long flatworm possess something at one end of the body crudely approximating a brain.

In man, however, the elaboration of the brain took a decisive turn. Out of its maze of incredibly complex matter arose the gift of language, enabling us to communicate, to share ideas as well as food and shelter. Experience, stored in the brain as memory, now could be passed down from generation to generation. A new kind of evolution, controlled by the brain, commenced. With it we have created, within only the past ten thousand years or so, the great edifice of civilization, vastly extending our cerebral gifts—machines to supplement our sensory and motor capabilities, housing to augment our built-in temperature mechanisms, taboos and laws to control instinctive emotions and drives, books and computers to aid memory.

The human brain is the most complex clump of universal matter known to exist. It is the perfect example of the exquisite extent to which matter in the universe has evolved—as far as we know. Yet is it the pinnacle of cosmic evolution? Is it not possible to philosophize about coagulates of matter more intricate than the brain, more complex than a clump of matter capable of contemplating itself? Just think of it—the brain can contemplate the brain, just as we are doing here now! In short, the brain provides for us a tool, a living apparatus to reflect back upon the material universe from which that life arose. One then can ask: Where will evolution lead us? What is our future? In particular, what is the longevity of our civilization?

FUTURE

Our future, the future of the planet, is cloudy, shrouded in numerous crises, many of which threaten the continued existence of Earth civilization and perhaps Earth life itself. The steeper-than-exponential growth of population, the rapid depletion of natural resources, the apparent hell-bent desire to harm ourselves via nuclear warfare, and the genetic degeneration of our medically oriented society, among other things, will lead irreversibly either to self-destruction, if we fail to solve any one of these problems, or to a state of mental stagnation resulting from the increasing degree of regimentation and depletion of freedom necessary to solve them. Of course stagnation implies a lack of curiosity, and then naturally one can ask: If curiosity dies, does intelligence die also?

It is important to realize that the problems we face today are not similar, not even in principle, to those of previous generations. The recent exponential rise in technological achievements and the inability of society to cope with them have led to problems basically different from those confronting earlier civilizations. Unlike years past, we now are approaching definite natural limits that even technology of the future will not be able to overcome. We cannot communicate faster than light; we cannot travel about the earth faster than orbital velocity; we cannot solve the population problem by emigration into space; we cannot consume fuel at the rate capable of increasing the average Earth temperature by one degree and thereby melting the polar ice caps; and, with respect to weapons capabilities, we cannot be deader than dead. We are in a transition period that no Earth society ever has encountered. This is not a doomsday forecast but a statement that social and political organizations appear unprepared to deal with the widespread changes necessary for our continued existence.

Then how can we survive? Actually it is easy. We simply become more intelligent!

But can we do so rapidly enough to resolve future crises, several of which are upon us right now? Well, some researchers have suggested that the key to survival may be to strive toward a higher level of consciousness, to attempt to achieve what probably will be the last great evolutionary leap forward—making contact with extraterrestrial intelligent life and thereby entering into the community of galactic civilizations. This is not to suggest that contact itself will provide for us instantaneous intelligence (though it might) but that the very program of searching will stretch our curiosity, widen our horizons.

Remember, if the processes of cosmic evolution outlined here are valid, then they apply to every nook and cranny of the universe. And, although there is at present no concrete evidence of the existence of intelligent life elsewhere, straightforward and reasonable arguments can be made to justify the plurality of habitable planets within our Milky Way and other galaxies beyond. But are they inhabited? We do not know of course.

A multinational surveillance program dedicated to the search and discovery of extraterrestrial intelligence may well be the proper program to pursue, giving us the advantage of competition and averting the danger of ultimate stagnation. Interstellar dialogue surely would enable our civilization to evolve toward heretofore unimagined heights. And in the long run, should our civilization survive, it is not inconceivable that life could evolve sufficiently to overwhelm matter, just as matter eventually overwhelmed radiation in the early universe. The destiny of matter in the universe may well be controlled ultimately by the life that arose from it. Together with our galactic neighbors, we may be in a position someday to gain control of the resources of the entire universe, rearchitecturing the universe to suit our purposes and, in a very real sense, ensuring for our civilization a sense of immortality.

The critical consideration for us in the years ahead is this: When a civilization tries repeatedly to solve numerous crises that inevitably face an evolving society and in doing so plunges straight toward mental stagnation—the crisis that ends all crises—will there be enough time to establish interstellar contact? Such a project obviously requires a good deal of financial enthusiasm and social commitment to sustain a search for tens, perhaps thousands of years. We may have evolved from universal matter, but our future is to a larger and larger degree in our own hands. Are we smart enough to recognize this alteration in the evolutionary scenario? Are we smart enough to ensure our own survival? Our future truly will be a measure of our current intelligence.

The philosophy that we are the product of cosmic evolution is not a new one. It may be as old as that first *Homo sapiens* who contemplated existence. But well into the last quarter of the twentieth century we can begin to identify conceptually and to test experimentally some of the subtle astrophysical and biochemical processes that enable us to recognize the cosmos as the ground and origin of our existence. It is very much an interdisciplinary approach, interweaving knowledge from virtually every subject a university can offer. It is a warmer and friendlier scenario now, many parts of which recently have become substantiated by experimental science. We are not independent entities, alien to Earth. Earth in turn is not adrift in a vacuum unrelated to the cosmos. The cosmos itself is no longer cold and hostile because it is our universe. It brought us forth, and it maintains our being. We are, in the very literal sense of the words, children of the universe.