# Three Eras of Cosmic Evolution

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*This conference-opening paper sketches the global hypothesis that permeated the discussions at this interdisciplinary meeting, the purpose of which was to explore prospects for research into the nature and distribution of life in the Universe.*

A friend who is a high-energy physicist once suggested that everything of importance happened within the first few minutes of the Universe. All subsequent events, he claimed, can be regarded as mere detail. Many scientists would regard my friend's view as provincial. The relatively simple subatomic matter may have been created in the first moments of the Universe, but the more complex organized matter now surrounding us must have formed well after its start. Every dating technique developed by post-Renaissance science suggests that complexity steadily arises from simplicity, order from chaos.

Granted, the initial coagulation of matter from otherwise chaotic radiation shortly after the Universe flashed into existence was an event of incomparable significance. This emergence of matter as the dominant constituent is the first great transformation in the history of the Universe. But a second great transformation occurs when technologically competent, intelligent life emerges from that matter. Our civilization on Earth is now on the threshold of this second transformation.

## EARLY UNIVERSE

To place the construction of all matter into perspective, consider figure 1, which summarizes the run of density and temperature throughout all time for a Big-Bang Universe. It represents the consensus of contemporary

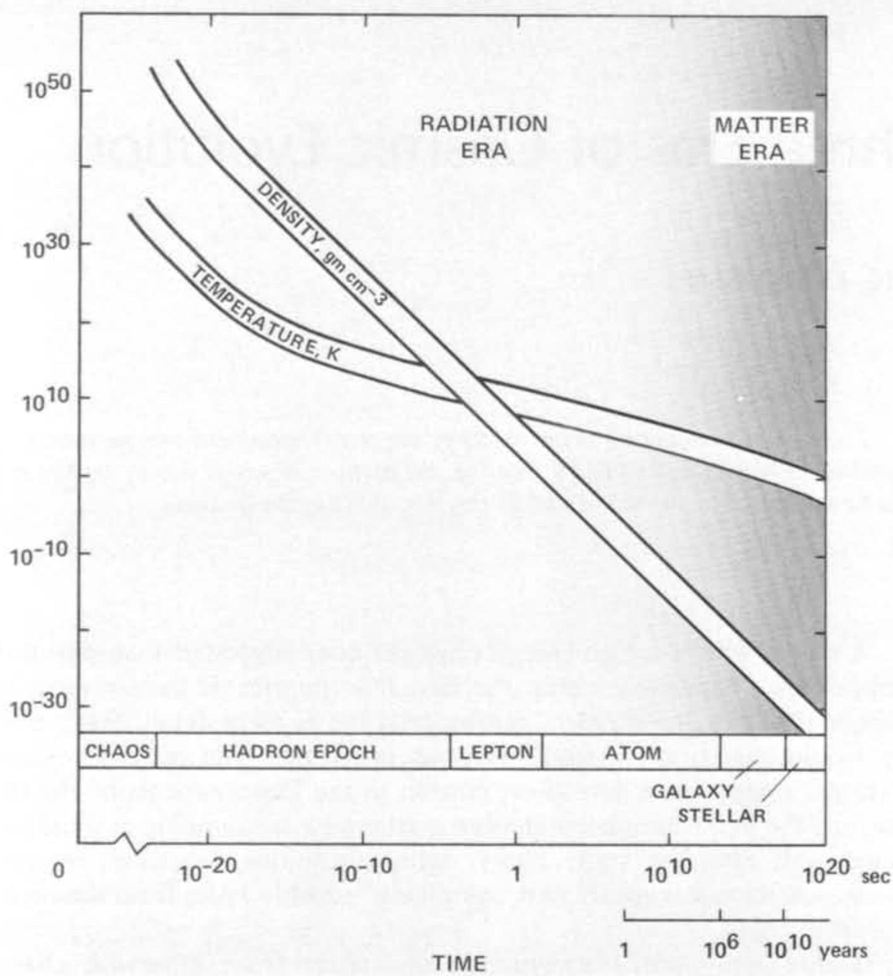


Figure 1. *Time variation of density and temperature for the Big-Bang model of the Universe.*

scientific thought in the broadest sense. Six major epochs are delineated, each corresponding to a major period in the history of the Universe. Specified across the bottom of this figure are the general names of the epochs, along with their time domains. Note that this plot is highly nonlinear, stretching from an incredibly small fraction of a second to the present time, 18 or so billion years after the origin of the Universe. The curves depict the *average* density and the *average* temperature of everything in the Universe at any point in time.

This figure suggests that in the beginning there was chaos. One cannot inquire about what happened at the exact moment of the Bang (precisely zero time). Some theorists argue, however, that it is possible to characterize the physical conditions at some extraordinarily small time after the Bang. For example, the currently known laws of physics specify a Universe younger than $10^{-23}$ sec to be characterized by an average density greater than $10^{50}$ gm/cm$^3$ and an average temperature greater than $10^{30}$ K. Of course, it is virtually impossible to appreciate such youth, for $10^{-23}$ sec is the amount of time it takes light to cross a proton. Equally difficult to comprehend are the large densities and temperatures characterizing this earliest epoch. The composition of the Universe at this time was indescribable, and its dominant action unimaginable.

The second major epoch is a bit closer to our limits of comprehension, although it is still characterized by severely nonterrestrial conditions — the *hadron epoch.* The name is derived from the fact that the heavy elementary particles such as protons, neutrons, and mesons, which were the most abundant type of matter at the time, are collectively known as hadrons. Calculations suggest that such particles existed as free unbound entities, considering the high temperature prevalent in the Universe well within its first second of existence. The hadrons unquestionably collided and interacted with one another and with other types of elementary particles, for the density was also extreme. The dominant action at this time is presumed to be the self-annihilation of hadrons into high-energy photons, thus creating a brilliant fireball of radiation. Lacking a solid understanding of elementary particle physics, scientists presently know very little more about this mystifying period.

As the Universe continued its rapid expansion, its contents cooled. A variety of models suggest that about a millisecond after the Bang, the conditions suitable for hadron annihilation had nearly subsided, thus allowing the initially less abundant, lighter elementary particles such as electrons, neutrinos, and muons to predominate. The average density and temperature of this *lepton epoch* had decreased to about $10^{10}$ gm/cm$^3$ and $10^{10}$ K. These physical conditions are still excessive by terrestrial standards, but they had diminished considerably compared to the chaotically dense and hot conditions extant a fraction of a second earlier. By the time the first second had elapsed, the leptons were self-annihilating into photons, much as had the hadrons earlier. The radiative fireball of the cosmic bomb was still being fed with new photons.

The radiation density exceeded the matter density by a large amount in these first few minutes; photons of radiation far outnumbered particles of matter. As soon as the elementary particles of matter began to coagulate, fierce radiation destroyed them. For this reason, the first three epochs are often collectively referred to as the *radiation era.* Whatever matter existed was merely an inconspicuous precipitate suspended in a sea of dense, brilliant radiation.

## LATER EPOCHS

The fourth epoch – the *atom epoch* – extends in time from about 100 sec to about a million years after the Bang. Midway through this epoch, the average density had decreased to about $10^{-10}$ gm/cm$^3$, while the average temperature had fallen to about $10^6$ K – values not terribly different from those in the atmospheres of stars today. A principal feature of the atom epoch was the gradual diminution of the original fireball, for the annihilation of hadrons and leptons had all but ceased.

Toward the beginning of the atom epoch, radiation still reigned supreme over matter, for the Universe remained flooded with photons. As the Universe expanded, however, the photon density decreased as the fourth power of the radius of the Universe, while the matter density decreased only as the third power. The early dominance of radiation thus gradually diminished. Sometime between a few minutes and a million years after the Bang, the charged elementary particles of matter were able to coagulate electromagnetically without being broken apart by radiation as quickly as they combined. This was a most important transformation in the history of the Universe. The dominance of radiation had subsided, for matter had gradually become neutralized, a physical state over which radiation has little leverage. Matter had, in a sense, overthrown the cosmic fireball. Henceforth it would dominate radiation as the principal constituent of the Universe. To denote this major turn of events, the last three epochs in figure 1 are collectively known as the *matter era.*

Once the matter era began, atoms appeared. The influence of radiation had grown so weak that it could no longer prohibit the joining of the leptons and hadrons that had survived annihilation. Hydrogen was the first element to form, since it required only that single electrons be electromagnetically joined to single protons. Copious amounts of hydrogen were synthesized in the early Universe, and it is thus the common ancestor of all things.

Hydrogen was not the only kind of atom formed early in the matter era. Indeed, at the start of the atom epoch, the average temperature of the Universe still exceeded the $10^7$ K necessary to fuse two hydrogen atoms into helium via the proton-proton cycle. The Universe was cooling, but it took time for the average temperature to dip below this critical value. Consequently, some helium atoms must have been produced within the primordial fireball in the same way that they now form in the interior of stars.

Elements heavier than helium, on the other hand, could not have been produced in the early Universe. The synthesis of such elements requires temperatures even greater than $10^7$ K. It also requires lots of helium atoms, for the heavier elements are constructed from lighter ones. The basic difficulty here is that, even though helium atom production was in high gear during the start of the atom epoch, the average temperature was falling quickly. Theoretical calculations suggest that, by the time there were sufficient helium atoms to interact with one another to produce the heavier elements, the temperature had fallen below the threshold value ($\sim 10^8$ K) required for the mutual penetration of doubly charged helium nuclei. In contrast to the rapid cooling of the early Universe, the dense interiors of stars in the present Universe are perfectly suited for the generation of hotter temperatures and thus heavier elements. The guts of stars are indeed where the heavies were created — and where they are still being created.

By the end of the atom epoch, matter was in firm control. Sometime during the fifth or *galaxy epoch,* gravity began to pull some of this matter together into enormous clumps. Galaxies were beginning to form. Indeed, they all must have originated long ago, for observations imply that no galaxies have formed within the past 10 billion years or so. Each galaxy contains substantial numbers of old stars, in addition to an often abundant complement of young stars. The quasars and remote galaxies must have formed in the earliest parts of this epoch.

The time scale of the last two epochs shown in figure 1 has been compressed enormously. An important and rapid series of events occurred immediately after the Bang, especially in the first few minutes that constitute the radiation era. However, once the Universe cooled sufficiently to allow atoms to form, subsequent events occurred more slowly.

By the middle of the galaxy epoch, the average density of the Universe had decreased by another factor of 10 billion, to $10^{-20}$ gm/cm$^3$. The average temperature of the entire Universe had also diminished to a relatively cool 3000 K. The Universe was becoming thinner, colder, and darker.

Finally, there is the present *stellar epoch.* Scientists can say with some assurance that it has been at least 10 billion years since the Bang. In fact, the Universe is probably older than that, perhaps as old as 18 billion years, although its precise age depends on the yet-to-be-determined change of the Hubble constant with time. The present average density is approximately $10^{-30}$ gm/cm$^3$, the critical value above which the Universe will eventually contract and below which the Universe will expand forever. The average temperature of everything in the Universe is presently 3 K. This then is the cooled relic of the incredibly hot fireball that existed eons ago, the fossilized grandeur of a bygone era.

The dominant action of the stellar epoch is the formation of stars, intermediate in size between atoms and galaxies. Research during the past several years has provided direct observational evidence that stars are actually forming within galaxies. Galaxies themselves are not forming in the present epoch, but stars within them apparently are — 18 billion years after the Bang.

An interesting by-product of star formation is the associated coagulation of matter into planets, life, and intelligence.

This history of the Universe is the prevailing view among most cosmologists. All theoreticians do not agree on specific events before about 1 sec. Depending on the intricacies of the model chosen, the density and temperature during the radiation era can change by several orders of magnitude. In virtually all models, however, the Universe is regarded to have been initially very hot and dense, after which it cooled and thinned.

## COSMIC EVOLUTION

The history of the Universe can be viewed in another way, one that follows a more linear time scale. Figure 2 shows the arrow of time, along which are marked several important developments in the history of the Universe. Known popularly as the scenario of cosmic evolution, it links the development of galaxies, stars, heavy elements, life, intelligence, technology,

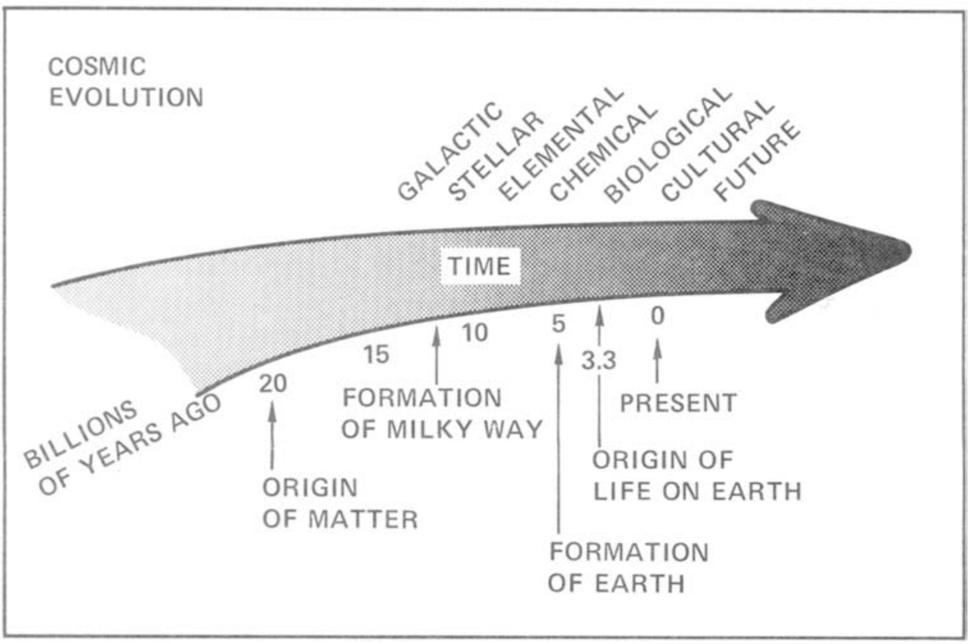


Figure 2. *Diagrammatic representation of the scenario of cosmic evolution.*

and the future. This diagram highlights the grand synthesis of a long series of gradual alterations of matter, operating over almost incomprehensible space and time, that have given rise to our Galaxy, our Sun, our planet, and ourselves.

Cosmic evolution is the study of the seemingly endless changes in the composition and assembly of various aggregates of matter and life throughout the Universe. It attempts to demonstrate that a clear thread links the evolution of simple atoms into galaxies and stars, of stars into heavy elements, of those elements into the molecular building blocks of life, of those molecules into life, of life into intelligence, and of intelligent life into culture and technology.

The scenario is supported handsomely by legions of experimental tests in physics, chemistry, biology, astronomy, geology, anthropology, neurology, sociology, and a spectrum of other disciplines. This support is general, however. We do not yet know all the details. Nor do we know much about either the starting or end points – the origin and destiny of the Universe. We do know that the Universe is not static: it is changing with time – it is evolving.

The scenario of cosmic evolution is a human invention. Despite seven major construction phases, it was not handed to us on a granite slab. Accordingly, it is subject to change as research progresses. As it stands now it is a broad guide to an understanding of the time evolution of matter, based on every available dating technique – not just methods utilizing radioactivity and fossilized life forms, but also self-consistent methods enabling us to date astronomical objects throughout the observable Universe.

Cosmic evolution stipulates that complexity arises from simplicity. It seems straightforward enough: light, quarks, atoms, stars, planets, life, intelligence – an entire hierarchy of material coagulations from radiation, to matter, to life. Yet this increase in complexity over time bothers some researchers because it seems to violate the second law of thermodynamics, which dictates that entropy (or disorder) should be increasing everywhere. Why should organization arise naturally from simplicity? In other words, why does entropy seem to decrease at certain selected locations within a universe where it is otherwise increasing? Frontier research suggests that the answer concerns the extent to which a system departs from thermodynamic equilibrium. A living organism, for example, is an open or unstable system, not in equilibrium with its environment. It resembles a heat engine that also concentrates energy. Consequently, life can construct and order itself by exchanging energy with the outside. Recent advances at the boundary between physics and chemistry suggest that classical thermodynamics, which predicts strict adherence to the second law, is restricted to systems in or near thermal equilibrium. These are closed systems, and their contents do indeed become disordered with time. Far from equilibrium, however, no system is stable, and this instability can lead to the occasional emergence of ordered macroscopic structures. It would seem then that the existence and organization of galaxies, stars, planets, and life are the result of energy having been captured by material systems far from equilibrium. Generally, destruction of structures occurs when they are near equilibrium, while construction of structures may occur when they are beyond some stability threshold.

## SOME MISSING LINKS

Cosmic evolution is a broad working hypothesis that attempts to integrate all that is known into an overall framework of understanding. However, several of the details within that framework remain to be unraveled. These are important details, for without a specific understanding of each of the major evolurionary events, we can never hope to comprehend this all-encompassing view of our Universe.

Curiously, it seems that valuable insight into many of these unsolved, largely cosmic problems can be gained by adopting a highly interdisciplinary approach and studying phenomena almost completely out of context. Consider a few examples.

### Galaxy Formation

The origin of the galaxies may constitute the biggest missing link in the entire scenario of cosmic evolution. Conditions at the present epoch of the Universe seem entirely inappropriate for the formation of galaxies. No observer has ever unambiguously reported evidence for galaxies forming at the present epoch, and no theorist can realistically suggest how they might do so given the present temperature and density throughout the Universe. Clearly, the hotter gas, more intense radiation, and greater turbulence of the early fireball were more conducive to galaxy formation; but specifically how they formed remains a mystery.

Contemporary researchers approaching this problem usually begin with the complex subject of hydrodynamics and examine the fate of density inhomogeneities in a turbulent medium. Since Earth's weather is a good example of turbulent gas flow, it is not inconceivable that studies of terrestrial phenomena may help us understand this extraterrestrial problem. Figure 3(a) shows the kilometer-sized swirling eddies that appear and disappear at random within Earth's atmosphere. These enhanced fluctuations in gas density become pronounced whenever air currents are particularly turbulent. Once in a while such an eddy can accumulate large quantities of moist air and grow into a full-fledged hurricane hundreds of kilometers across (fig. 3(b)). Although on a much smaller scale, this terrestrial phenomenon roughly mimics the overall morphology, the pancake shape, the differential rotation, and the concentration of energy within spiral galaxies (fig. 3(c)), which are thought to have formed by accumulating gargantuan quantities of hydrogen gas. Of course, meteorological conditions on Earth have no direct bearing on the origin of galaxies, but their several resemblances suggest that something can be learned about galaxy formation through the study of hurricane formation. In particular, since most meteorologists agree that some sort of turbulent "priming" is required to initiate a hurricane, the early stages of such storms could conceivably be used by astronomers to derive clues about the elusive density fluctuations that gave rise to protogalaxies in the early Universe.

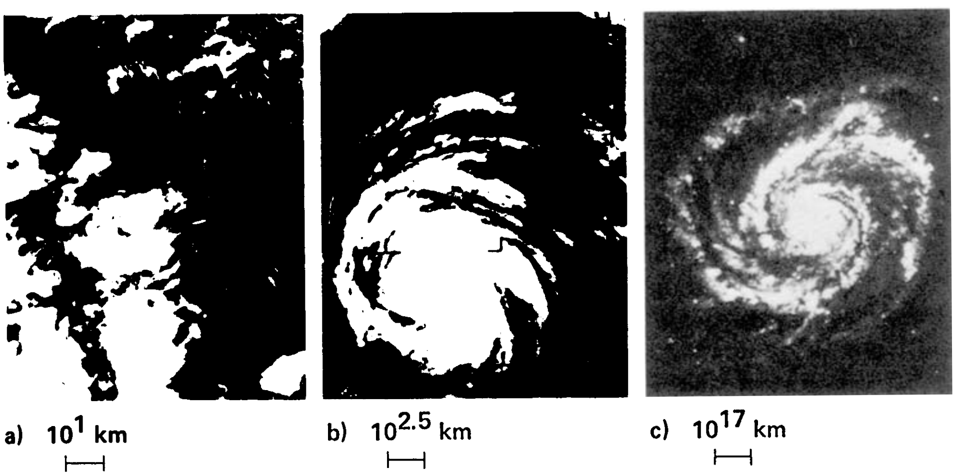


Figure 3. *(a) A Skylab photograph of the top of Earth's cloud layers, showing the presence of several atmospheric eddies near the Canary Islands. (b) A full-scale hurricane is a collection of moisture hundreds of times larger than an atmospheric eddy. In 1967, Hurricane Beulah was photographed by one of the ESSA satellites hovering over the Gulf of Mexico. (c) A spiral galaxy is a collection of mostly gas, usually more than a trillion times larger than a hurricane (M51; Harvard Observatory).*

## Origin of Life

Clues to the physical and chemical conditions on primordial Earth might similarly be gleaned from the study of cell-like organic ensembles synthesized under laboratory conditions. The production of some amino acids and bases from a primordial mixture of ammonia, methane, water, and energy has been known for some time. More sophisticated experiments in recent years have shown that repeated heating and cooling of simple organic molecules can yield spherical droplets that contain large concentrations of complex polymers. These are not proteins as we know them, but simpler proteinlike linkages of amino acids.

Figure 4 is a photomicrograph of a few of these so-called proteinoid coagulations. Although there is some dispute regarding the relevance to primordial Earth conditions of the laboratory experiments used to produce these proteinoids, the coagulations do seem to resemble morphologically some of the most ancient microfossils as well as modern blue-green algae cells. These curious chemical proteinoids appear to possess many of the attributes of bona fide living organisms: they are cell-like spheres a few microns across, each possessing a thick shell-like membrane; most even appear to exhibit a primitive metabolism, with some dissipating away while others swell and bud (fig. 4). This is not to suggest that the proteinoids should be in any way associated with life itself. Rather, because their physical and chemical properties so closely mimic those of procaryotic cells, the suggestion here is that researchers ought to be able to glean some insight into the ways and means of chemical evolution through further study of these proteinoid globules, despite the controversy over the appropriateness of the initial laboratory conditions. The laboratory proteinoids may be as far removed from real life as hurricanes are from galaxies. But their overall morphology and their microscopic kinetics suggest some resemblance to whatever were the progenitors of living organisms on Earth. Laboratory studies of such protocells may someday have reverse usefulness by demonstrating what Earth was like some 4 billion years ago.

## Chemical Evolution

As a third example of how one research specialty might be taken somewhat out of context to study a seemingly unrelated problem of cosmic evolution, consider chemical evolution. The study of interstellar molecules may well yield some insight into the origin of life on Earth. This is not to suggest that interstellar molecules have any direct bearing on the onset of terrestrial life, but studies of galactic clouds could allow us to recover information about the early stages of chemical evolution lost forever on our planet.

Dark and dense interstellar clouds (fig. 5) may in fact rank on par with the Jovian atmosphere as the best place to study chemical evolution. These clouds are rich in a variety of small molecules such as carbon monoxide (CO) and formaldehyde ($H_2CO$), compounds typically five orders of magnitude less abundant than molecular hydrogen ($H_2$). These and other molecules are

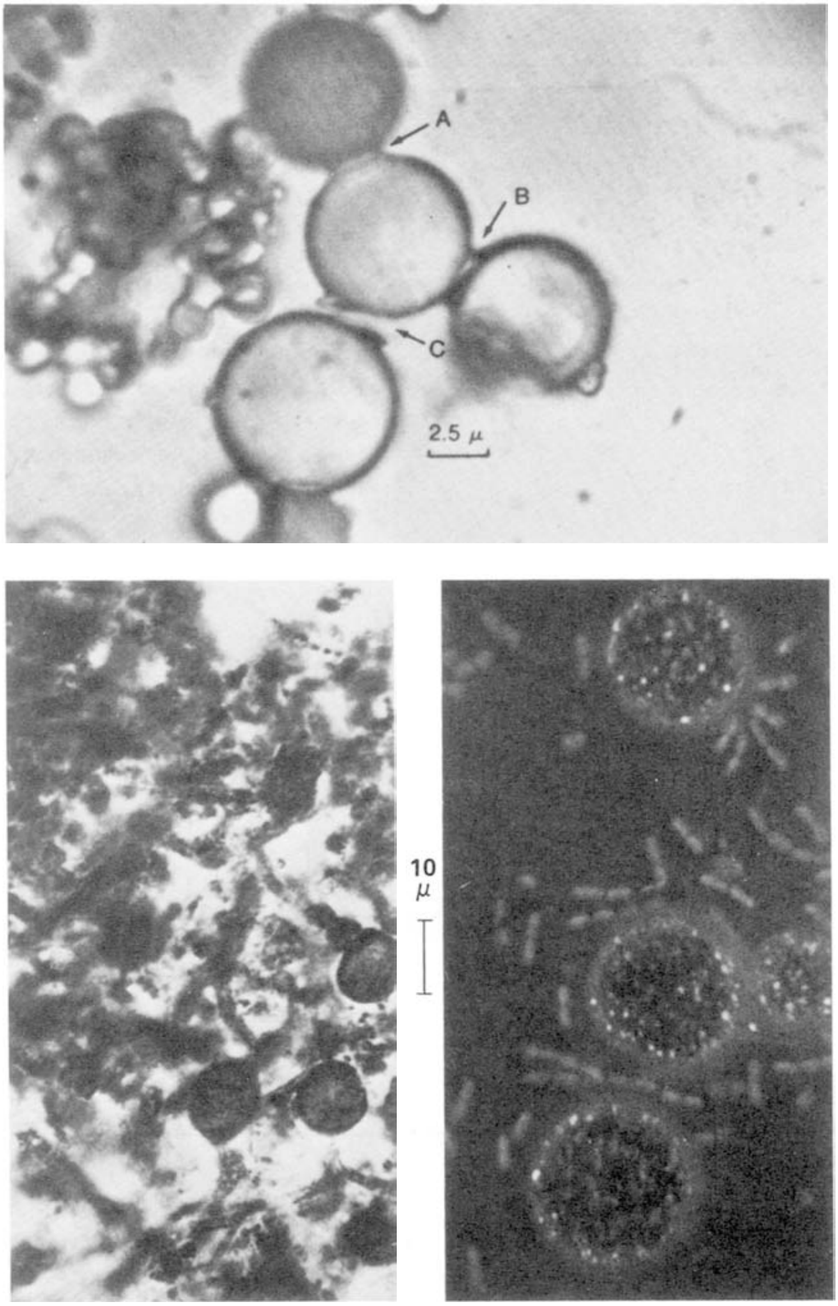


Figure 4. *A photomicrograph of proteinoid spheres, each containing a large concentration of amino acids (upper frame; from the research of S. W. Fox and his associates). Very old fossils, dated to be about 3 billion years old (left bottom frame; from the research of E. S. Barghoorn and his associates). Simple blue-green algae cells found almost anywhere on Earth (lower right frame).*

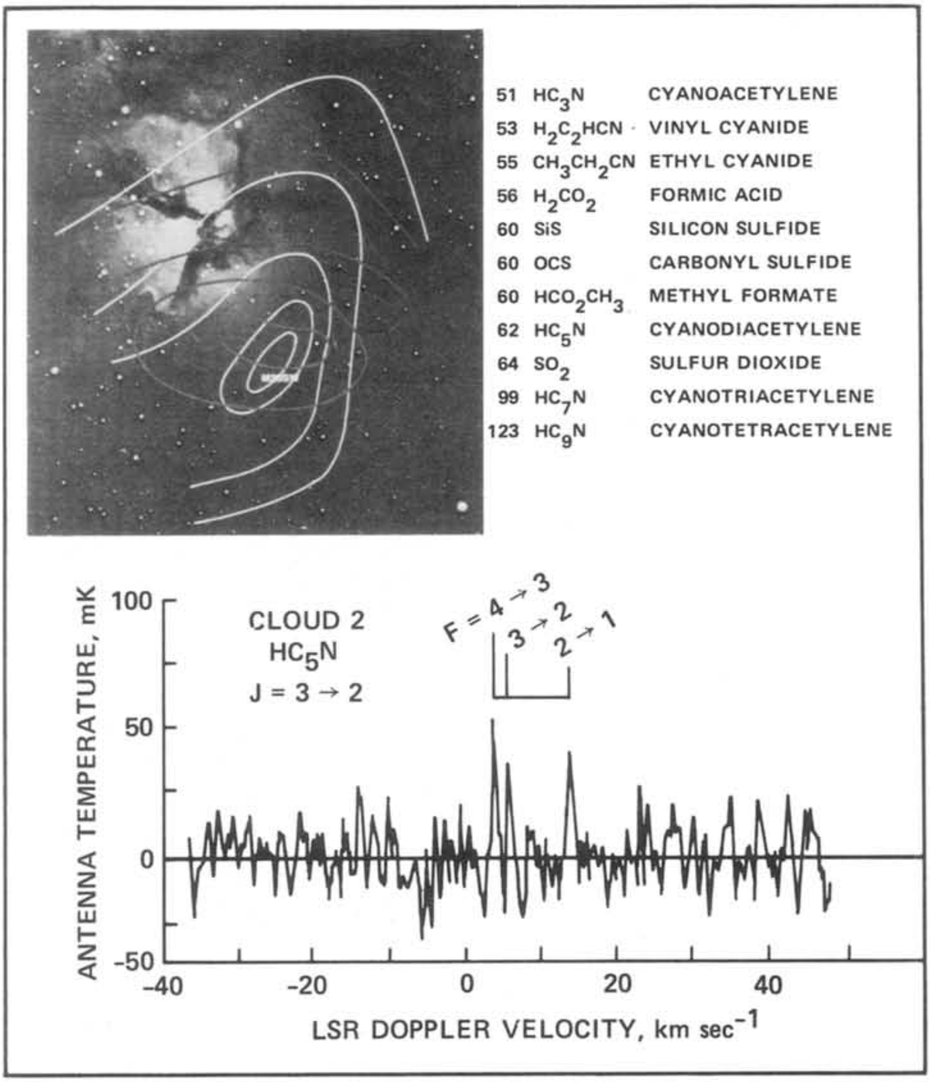


Figure 5. *Typical dark, dense, and dusty interstellar clouds can be seen outside the glowing Trifid Nebula. The contours show the distribution of several molecules within a particularly rich cloud known as M20SW (left top frame; photograph from Harvard Observatory; contours from author's research). Nearly a dozen interstellar molecules having masses greater than 50 atomic mass units had been observed by mid-1979 in the interstellar clouds of our Galaxy (right top frame). The unique hyperfine spectral features of the $HC_5N$ molecule were observed at 8 GHz toward an interstellar cloud with the 1000-channel spectrometer of the Haystack Observatory (bottom frame; unpublished data by author and his associates).*

invariably found in regions containing large concentrations of dust, suggesting that dust plays either the role of catalyst in the formation of the molecules or the role of protector once the molecules form by some other mechanism. In addition, spectral lines characteristic of much heavier molecules have been detected in localized patches of these giant molecular clouds, which routinely span tens, sometimes hundreds, of light years. For example, about a dozen interstellar molecules are known that have a molecular weight exceeding 50 atomic mass units. These include many of the familiar products of the laboratory simulations of primordial Earth conditions: cyanoacetylene ($HC_3N$), formic acid ($H_2CO_2$), and several others listed in figure 5, presently topped off by cyanotetraacetylene ($HC_9N$). More than 50 interstellar molecules have been identified, and nearly 200 more as yet unidentified features have been observed, mostly in the millimeter-wave spectrum of interstellar clouds.

The greatest significance of these heavy molecules is that they exist in space. Apart from this, they are also significant because of their unexpectedly large abundance, often within 8 to 10 orders of magnitude (by number) of $H_2$. The observed spectra leave little doubt about their identification or their relative abundances. For instance, figure 5 shows a recently acquired high-resolution spectrum of the hyperfine transitions of the $HC_5N$ molecule. Because the observed line strengths agree with the quantum-mechanical predictions for spontaneous emission, the measured intensities cannot be appreciably amplified by masing or other non-LTE processes. The very fact that such signals are detectable suggests that these heavy molecules are far more abundant than anyone would have guessed even after the rash of discoveries of interstellar molecules began about a decade ago.

While the consensus still maintains that the larger molecules are probably constructed from smaller atoms and molecules already extant in interstellar space, there is at present no satisfactory formation mechanism for the large organic coagulations now found there. Consequently, some researchers are beginning to consider seriously the possibility that some interstellar molecules could result from destruction rather than construction; that is, many of the interstellar molecules now observed may be fragments torn from much larger molecules yet to be detected. A statement once offered as a lark, namely, that the enigmatic interstellar dust grains have the same dimensions as virus particles, may in the end turn out to be prophetic. If so, the interstellar cloud could become the key to our understanding not only of the early stages of chemical evolution, but of the advanced stages as well.

## Other Missing Links

It is not inconceivable that we could learn more about several of the other missing links of cosmic evolution by studying phenomena normally considered outside the realm of traditional investigation. New insight into the origin of our solar system is now being provided by radio and infrared observations of protostellar regions scattered throughout the Milky Way Galaxy. Major advances concerning the origin of human intelligence have been made by studying the behavior and learning abilities of the great apes. And the physical conditions close to the birth of the Universe itself may someday be appreciated by studying the death of such supermassive objects as black holes.

## LIFE ERA

It is hard to condense 18 billion years of history into a few paragraphs. Figure 6 shows the broadest view of the largest picture. Radiation dominated matter in the earliest epochs of the Universe. The enormous number of

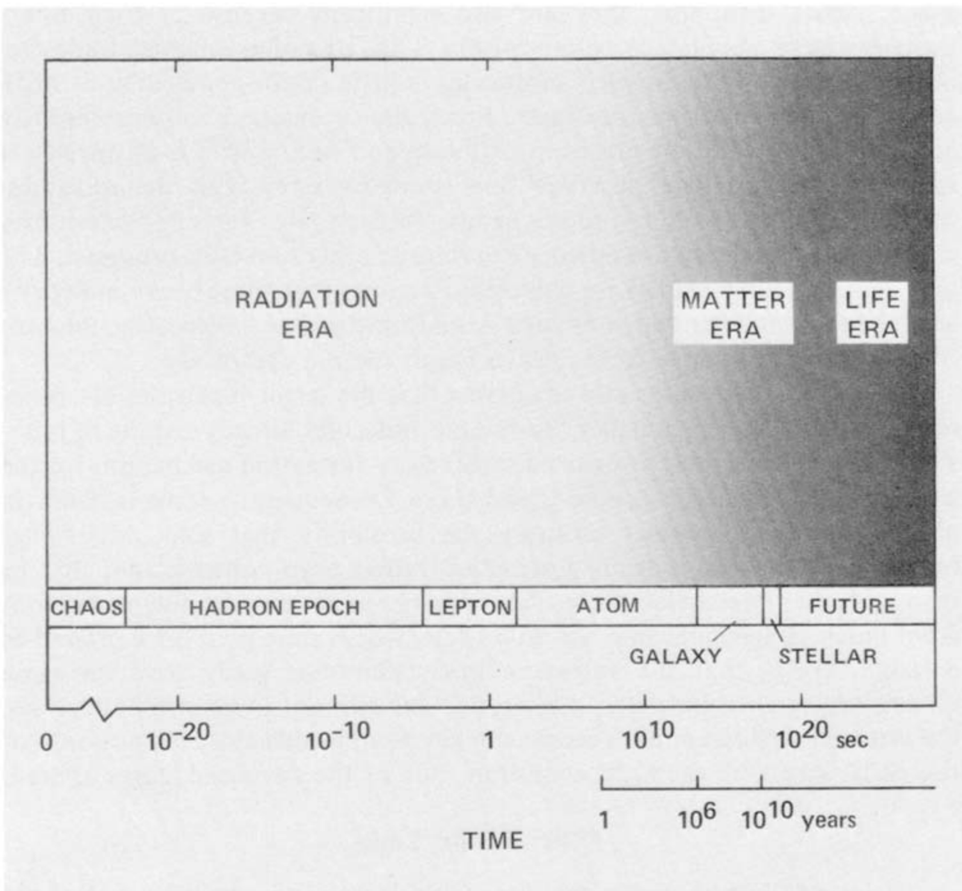


Figure 6. *Three principal eras of cosmic evolution.*

photons, and particularly the scattering of photons by the electrons, produced a fireball inside of which no atoms or molecules could have formed.

Slowly, as the Universe expanded, it cooled. Matter gradually began to coagulate into atoms and eventually into clusters of atoms. From the start of the matter era, matter dominated radiation, and it has dominated radiation ever since, successively forming galaxies, stars, planets, and life.

Life forms are most interesting pieces of matter, especially technologically intelligent ones. One can argue that technologically intelligent life is fundamentally different from lower forms of life and other pieces of matter scattered throughout the Universe. It is fundamentally different because it can tinker not only with matter but also with evolution. For example, whereas previously the gene (i.e., DNA) and the environment (be it stellar, planetary, geological, or sociological) had governed evolution, now we on Earth are suddenly gaining control of both the gene and the environment. We are now tampering with matter, diminishing the resources of our planet, often polluting it. And we are now on the verge of tampering with life, potentially altering the genetic makeup of human beings.

The emergence of technologically intelligent life heralds a whole new era — a *life era* — as suggested in figure 6. Technology enables life to begin to control matter, much as matter grew to dominance over radiation tens of billions of years ago. Matter is now losing its total dominance, at least at those isolated locations where technologically intelligent life resides.

The transformation from a matter era to a life era will not be instantaneous. Just as it took time for matter to dominate radiation in the early Universe, it will surely take a great amount of time for life to dominate matter. And, in fact, such domination may never be total, either because civilizations may never control resources on a truly galactic scale or because the longevity of technological civilizations may be inherently small. But one thing seems certain: we on Earth, as well as other intelligent life forms throughout the Universe, are now participating in a fantastically important transformation — the second most important transformation in the history of the Universe.

We now stand on an enormously significant threshold. We have come full cycle. We have become smart enough to reflect back upon the material contents that gave life to us. Life now contemplates life. It contemplates matter. It ponders its own origin and destiny. It explores the planetary system we call home. It searches for extraterrestrial life. It quests for new knowledge.

Provided civilizations remain curious, provided they are wise enough to survive, then it is not inconceivable that life could evolve sufficiently to overwhelm matter, just as matter overwhelmed radiation in the early Universe. Indeed, the destiny of matter in the Universe may well be controlled in part by the life that arose from it. Together with our galactic neighbors, should there be any, we may be in a position someday to gain control of the resources of much of the Universe, rearchitecturing it to suit our purposes and, in a very real sense, ensuring for our civilization a measure of immortality.

## ADDITIONAL READING

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