2 The Origin of Life on Earth

Earth is a spectacular world. It is surely a pinnacle of creation within the Universe, and if our planet is not the Universe's crowning achievement, then an even more breath-taking Universe awaits us.

Our planet has thrived and developed persistently throughout its entire history. Despite events that have on occasion virtually obliterated all life and radically altered its surface, our world has emerged as one of exquisite balance between the gargantuan forces of the surrounding Universe and its own inner make-up, the result of which is the beautiful blue-green globe we now inhabit (Figure 11).

We have already encountered one of the grandest forces of all to affect our world—its quarter-of-a-billion-year journey around the galaxy. But there are many others, including a number of celestial cycles that alter the orientation and movement of our planet in relation to the Sun over timescales of thousands of years. These are known collectively as the Milankovitch Cycles in honor of the Serbian astronomer Milutin Milankovitch who determined many of their characteristics.

The best known of the Milankovitch Cycles is a precession of Earth's axial tilt where, over approximately 26,000 years, a gravitational pull by the Sun and Moon upon Earth's slight equatorial bulge will cause the orientation (but not the size) of the axial tilt with respect to the Sun to vary, just as a spinning-top slowly wobbles when rapidly spinning. For example, where currently the Earth's northern hemisphere tilts most *toward* the Sun at some particular point along its orbit, in approximately 13,000 years (or half of a precession cycle) the northern hemisphere will tilt *away* from the Sun at that same orbital position. Hence, as regular and small adjustments will be required to maintain our calendar over an entire precession cycle, the precession affects the position along Earth's orbit where particular calendar events occur. Another Milankovitch Cycle is called orbital precession where, over a period of approximately 70,000 years, the distant gravitational pull from the other planets causes Earth's orbit about the Sun to precess. This, coupled to axial precession, induces a 41,000-year cyclical change in the

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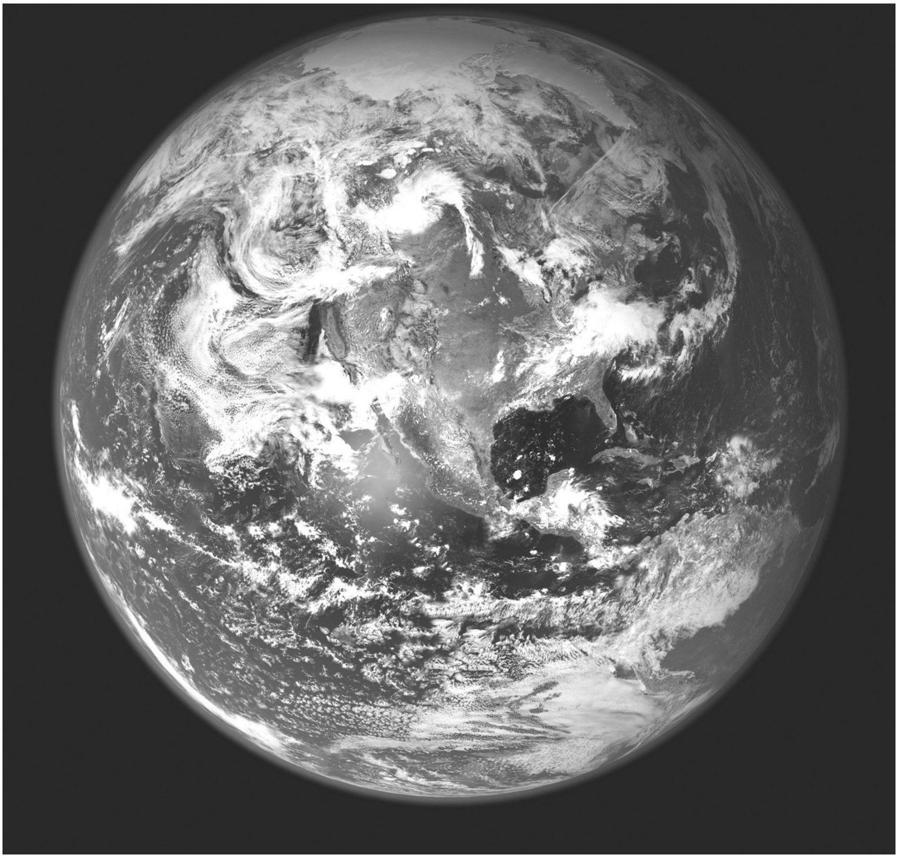

Figure 11: Earth—a spectacular and vibrant world whose legacy has been defined by internal and celestial forces. See Plate 4 in the color section. [Credit: NASA Earth Observatory]

size of Earth's axial tilt, called its obliquity, from a minimum of about 22 degrees to a maximum of approximately 24 degrees. Perturbations in the gravitational pull of the other planets also affect the roundness or eccentricity of Earth's orbit over a timescale of about 100,000 years, changing the shape of the orbit from a near perfect circle to an ellipse of about 5% eccentricity.

When combined, the various axial and orbital cycles can affect Earth's surface conditions quite significantly. Changes in obliquity, for example, affect the distribution of solar radiation upon the northern and southern hemispheres over time. Changes in eccentricity, on the other hand, affect the amount of solar energy each hemisphere receives along its orbit. At maximum eccentricity, a given hemisphere can receive up to 20% more energy at the Earth's closest point the Sun (called perihelion) compared to when furthest from the Sun six months later (called aphelion), while at minimum eccentricity the amount of energy received throughout the year is more even. Although not conclusive, there is increasing evidence to show that past changes to the world's climate, including significant events such as the ice ages, have been in part caused by the Milankovitch Cycles.

However severely such celestial cycles impact upon our world, they are far from the most significant of external influences. That honor belongs resolutely with our Sun. From the outset, the nature and evolution of our planet has been governed by our Sun's extreme stability over billions of years, coupled to our near-perfect distance from it, residing in the center of the Sun's habitable zone. Despite such idyllic conditions so conducive to life, the Sun also emits lethal doses of electromagnetic and particle radiation that could have severely curtailed life here were it not for Earth's own natural defences—a planetary magnetic field to deflect particle radiation, deep oceans to protect the first water-dwelling life, and a dense atmosphere that evolved to protect subsequent land-based organisms. Thus, while owing our very existence to the Sun, we are also at its mercy. Should the Sun change in any significant way, there can only be cataclysmic consequences for our planet. Although no significant change is expected for millennia, as the Sun grows older it also becomes more luminous, and its habitable zone extends outward accordingly. Consequently, in about a billion years the Sun's habitable zone will have expanded so far that Earth will reside in its inner region and become so hot as to cause the oceans to evaporate, turning our once beautiful blue-green world into a desolate place. Intriguingly, the planet Mars, currently orbiting on the far outer edge of the habitable zone, will then sit favorably within it, perhaps bringing a new vibrancy to that world. The Sun has provided for all that has flourished on Earth, but at some point in the distant future it will cease supporting any form of life. In solar terms, Earth is an aging planet with most of its vibrant life behind it. Our world has circumnavigated the Milky Way galaxy more than 20 times throughout its long history, but it will do so perhaps another four times before it expires.

Our Moon also casts a firm hand over our planet's nature and fate. The Moon is a planet-sized object and the Earth and Moon could almost be regarded as a double planet system. With no evidence of life, or indeed any indigenous surface activity, the Moon is a reminder that even when ideally placed from the Sun, many other planetary factors are required for life as we know it to exist. There is evidence to suggest that our Moon originally formed from a glancing-blow collision between the Earth and another Mars-sized planet in its earliest history, with the Moon taking shape from the remaining debris in only a matter of a few years and settling into an orbit some 20 times closer that it is today. However created, the Earth and Moon have been linked since their earliest history in a gravitational courtship which, through the influence of tidal forces, has radically altered both. Tidal forces occur because the side of our planet facing the Moon experiences a slight increase in gravitational pull, causing a minute flexing of the Earth's shape that produces an upward bulge of several centimeters on land and several meters within the oceans, both on the side facing the Moon and on the side pointing away from it. Because the Earth rotates more rapidly than the Moon orbits, the Earth's tidal bulge exerts a small extra gravitational pull as it moves ahead of the Moon, dragging it ever so slightly forward in its orbit. Conversely, the Moon pulls back on the bulge, slightly slowing Earth's rotation. The result is that energy is taken from Earth's rotation, slowing it by about 2 milliseconds per century (the Earth's day was probably about 6 hours long when the Moon first formed) and is transferred to the Moon's orbital motion, allowing it to drift outward at a rate of several centimeters per year.

Acting over billions of years, lunar tidal forces have been a major factor in shaping the surface of our planet, inducing daily mass movement of the world's oceans that brings about powerful and relentless planet-wide weathering, erosion, deposition, and their associated geochemistry. Critically, tidal forces between the Earth and Moon were in the order of 8,000 times greater in Earth's early history, no doubt affecting tectonic and volcanic activity, stirring the ocean violently and bringing about all manner of energetic surface activity, perhaps relevant to the emergence of life. There can be little doubt that in the absence of the Moon, Earth would have evolved with significantly different oceanic and climatic patterns and perhaps even a different regime for the biosphere and for life itself.

Another significant contributing factor to the character of our world is, of course, its own internal make-up and dynamics. At almost 13,000 kilometers across, our planet has been capable of sustained internal heat production throughout its entire history, generated both by gravitational contraction and from natural radioactive decay of heavy elements at the core. Slowly, heat emanates from the core to the mantle above, heating it to over 3,000°C. Despite such searing temperatures, sustained pressure from above keeps the mantle solid, but at just several hundred kilometers below the surface the upper mantle (called the asthenosphere) becomes plastic and ductile and is driven into gigantic convectively flowing cycles. The outermost layer, upon which Earth's crust sits (called the lithosphere), acts as a lid and responds to the convective currents below by cracking into a dozen or so tectonic plates. At plate boundaries, one plate slides under another in a process called subduction, while on its far side it is replenished from material rising from beneath, usually at mid-ocean ridges which then give rise to sub-aqueous hydrothermal vents, now seen as potentially important to the emergence of life. Over millions of years each plate undergoes drastic change and rejuvenation, creating and moulding continents and releasing huge quantities of water, carbon dioxide, and many other materials to the surface.

Biosphere

Despite the enormity of the forces bearing down from the vacuum of space and upward from the crushing interior, all have conspired to create an interconnecting zone of striking balance upon our planet. Starting at several kilometers below the surface and reaching to perhaps 30 kilometers above, this zone is called the biosphere because it is flourishing with life.

Among the major influences upon the biosphere is its volatile activity. Volatile materials include elements such as hydrogen, carbon, nitrogen, and oxygen as well as compounds such as water, carbon dioxide, methane, and ammonia. They are called volatile materials because they more readily change from solid to liquid to gas than other substances—for example, the changes that take place with water on the Earth's surface. By cycling though the various natural planetary reservoirs in response to changes in heat from the Sun (and from within the planet itself), volatile materials play a vital role in regulating and taming the biosphere while, in the process, bringing about the extraordinary dynamism that is so important to life.

One such cycle is called the hydrological cycle, which regulates Earth's supply of water across its rivers, lakes, seas, and oceans as well as within the crust, in the atmosphere, and polar ice caps. Significant transfers of water, especially between the oceans and the polar ice caps, are driven by changes to the global climate brought about by variations in solar insolation (that is, the amount of solar radiation incident on the Earth's surface). When the planet warms, water from the ice caps melts, with sea levels rising and precipitation increasing. Conversely, when the planet cools, water that finds its way to the polar regions freezes and remains there for thousands of years or more. Earth's hydrological cycle, as dynamic as it may be, is vital to stabilizing the climate, tempering the otherwise devastating effects that would arise from even small changes in the Sun's energy output.

Another key cycle is the carbon cycle, which regulates where and in what chemical form carbon resides—whether as organic carbon in living and dead organisms, as carbon dioxide in the atmosphere or dissolved in the oceans, or as carbonate sediments within the crust. In Earth's early history, carbon dioxide was a major constituent in the atmosphere, but over time virtually all of it has dissolved in the oceans and precipitated out as carbonate sediments. Hence, the carbonate sedimentary rocks within the landscape today are a testimony to an era long since past during which carbon dioxide was a dominant feature of the atmosphere. Despite the loss of all but trace levels, an important carbon dioxide cycle is still maintained today, driven by fresh supplies released from volcanic and tectonic activity, the weathering of carbonate rocks, and from human activity. Although comprising less than four hundredths of 1% of the atmosphere, carbon dioxide is vital to the stability of the planet as we know it, by acting as a heat shield, trapping solar radiation that would otherwise be reflected by the surface back into space. If it were not for such a natural greenhouse effect, Earth's surface would be over 30°C cooler at an average temperature of 18°C below the freezing point of water—too cold for pure liquid water to be sustained on the surface. It is therefore not just Earth's favorable distance from the Sun, but also the presence of trace levels of volatiles, such as carbon dioxide, that sustains our clement environment.

Most of the volatile materials found within our biosphere are also classed as biogenic materials because they are crucial to life. Hydrogen, carbon, nitrogen, and oxygen as well as water, carbon dioxide, and methane, among others, have been intimately linked with the operation of life throughout Earth's history. Indeed, many features on the surface of our world, including its volatile activity, reveal that it is dominated by life. The virtually planet-wide proliferation of vegetation, planetary oceans of liquid water, an oxygen-rich atmosphere, and even our particular weather and climate are all clear indicators of life being a significant feature of our world.

While the proliferation of plant and animal life across the globe is truly a crowning achievement within nature, we have recently become aware of other, significant, regimes of life hitherto unknown to us. For example, where we previously thought there were thousands, we now suspect that there are millions of species of microbial life comprising perhaps half of the total biomass of our planet. And while it was historically regarded as a simpler form of life, we now realize that microbial life is, in general, highly adaptable. Rapid reproduction rates and a high capacity for spontaneous genetic mutation allow microorganisms to adapt more rapidly to changing environments, making them ubiquitous across the biosphere.

Indeed, it seems that life on Earth has adapted to virtually every available niche. It is only in recent decades that entirely different types of ecosystems have been discovered in some of the most extreme environments on Earth, inhabited by types of organisms called extremophiles. For example, extremophile microorganisms have been found within the rocks of the coldest and driest deserts of Antarctica. Other types of extremophiles, called thermophile and hyperthermophile organisms, thrive in total darkness at temperatures well in excess of 100°C and at normally crippling pressures many kilometers down on the ocean floor, feeding from chemical nutrients from hydrothermal vents located at tectonic rifts. Ecosystems have also been found within the most acidic, alkaline, and saline environments known, and one microorganism, *Deinococcus radiodurans*, can even survive radiation dosages typical of nuclear reactors. As varied and extreme as Earth's environments can be, virtually all can support life. It seems that, historically, we have underestimated both the diversity and robustness of life and may continue to do so.

Life on Earth

The discovery of such extreme organisms and ecosystems has provided new insight into the nature of life in general and reveals an intimate connection between life and the planet itself that has perhaps not previously been fully appreciated. Of course we have known of such a connection since Darwin put forward the idea of evolution, but the discovery of extremophile life in particular demonstrates that life does not simply inhabit the world, but is intimately connected to the natural history of the planet as shaped both by its innate activity and its celestial environment. Evolution explains our natural history, by unifying the historical course of past life with the nature of the living world today, while also revealing its deep-rooted planetary connection.

Evolution proposes that an original ancestor—a single species—emerged in Earth's distant past and survived to reproduce within the prevailing planetary conditions. Minor alterations in traits (caused by random changes in genes involved with reproduction) led to successive generations, that had small genetic differences from their ancestors, eventually becoming different species.

Over millions of years, and spreading across the globe, life became evermore diverse, giving rise to a multitude of species. While, for some period of time, a species could cope with the prevailing conditions, significant changes to the environment would put that to the test, and only those that were fortunate enough to have a natural capacity to exist managed to survive. Through countless changes in the environment over Earth's long history, equally countless species have lived and then suffered extinction. On occasion, catastrophic tectonic, volcanic, and celestial impact events have altered Earth's surface so severely as to eradicate large portions of all life, changing its future course. Through relentless alterations to the biosphere, organisms with adaptations to every available niche have emerged, and if life now resides in the most extreme of environments, it is only because those environments were intrinsically involved in its diversification and adaptation from the outset.

The effect of evolution has not been all one way. Along with celestial and internal planetary forces, so too has the proliferation of life played a prominent role in shaping the surface of our world. For example, while our atmosphere now comprises over 20% oxygen, originally there was none. Only with the emergence of water-based photosynthesizing plant life was oxygen gas produced in significant quantities. Even then, oxygen is so chemically reactive that the total produced over the first two billion years reacted with metals dissolved in the oceans and within the crust, and only when Earth's surface was completely oxidized could surplus oxygen begin to accumulate within, and transform, our atmosphere.

Over the course of history, living ecosystems have radically altered the Earth's surface. Chemical alteration of the crust, atmosphere, and oceans, including the regulation of drainage, weather, and climate—and even in part sustaining the world's oceans, which themselves help to lubricate plate tectonic activity—are all outcomes of life. Earth's legacy is an ancient symbiotic relationship between life and the planet itself, both of which have undergone radical change and development over time, transforming our world into the finely tuned and complex one we now inhabit.

The Nature of Life

For hundreds of years we have attempted to classify the multitude of types of organisms now inhabiting our world in such a way as to reveal their underlying nature. An important recent classification was developed by the microbiologist Carl Woese in 1977, both in recognition of an increased understanding of genetics and of the discovery of extremophile life. Woese's classification encompassed three distinct and overarching branches of life called domains—archea, which were previously regarded as an ancient form of bacteria called archeabacteria, are now widely accepted as one of the three domains of all life, along with bacteria (otherwise known as prokaryotes) and eukaryotes.

Eukaryotes, which comprise the multicellular organisms such as plants and animals, are characterized by living cells with an internal membraneenclosed cell nucleus containing most of the cell's genetic material. Bacteria, on the other hand, are single-celled microorganisms whose genetic material is not contained within a nucleus but instead within the main body of the cell itself. Archea are similar in this respect, but are so different in many other aspects of their biochemistry as to be classified as an entirely separate domain of life. Archean microorganisms are of particular interest because they include many of the inhabitants found in extreme habitats such as sub-aqueous hydrothermal vents and hot springs. Furthermore, biochemical and genetic dating techniques suggest that archean life is closer than any other to the proposed original ancestor from which all other life on Earth arose.

While there is clearly enormous diversity in life, many important attributes are common to all life. For example, all life is characterized by at least five key functions: reproduction, metabolic activity, growth, evolution, and sensory response to stimulus from the surrounding environment. Such commonality points to a general definition of life according to function, independent of how those functions are carried out. And while rudimentary, such a definition is none the less of great value when investigating the legacy of life on Earth and when searching for life elsewhere in the Universe, because it gives indications of what to look for without having to know the fine detail of any such life, or its ecosystem, in advance.

We also find many striking common features in the underlying morphology and biochemistry of all life on Earth. As already indicated, all organisms, from the microscopic bacterium to the largest plants and animals, are built upon the cellular morphological unit. Furthermore, despite the enormous diversity and specialities in the roles of cells throughout life, all share many underlying characteristics, such as a fatty-protein semi-permeable outer membrane, and, among many others, an internal aqueous solution that concentrates the materials needed for (and which enables) life activity. Indeed, as we traverse the microscopic to the molecular levels at which the biochemistry of life operates, we again see striking commonality. For example, with the exception of some viruses, replication in all life on Earth occurs though the biochemical symbiotic relationship of deoxyribonucleic acid (DNA), ribonucleic acid (RNA), and protein-based enzymes.

DNA is an enormous molecule composed of billions of molecular building blocks called nucleotides. A nucleotide is composed of three molecules linked together—a pentose (5-carbon) sugar molecule, one or more phosphate groups and one of four types of organic bases: adenine, cytosine, guanine, and thymine. Nucleotides join together into enormous chains called polynucleotides. DNA comprises two polynucleotide chains connected together along their length, with adjacent bases linked together into base-pairs similar to the rungs of a ladder, which then twists into the famous "double helix" shape. While DNA contains the relevant genetic information needed for the various functions of life, it cannot carry out its own operations without the aid of RNA and enzymes. RNA, of which there are many types, is composed of a single polynucleotide chain, with the organic base uracil replacing thymine. Enzymes are composed of proteins that are themselves made of amino acids linked together into polypeptide chains.

DNA, RNA, and enzymes work together in the most exquisite of symbioses found in nature. First, DNA synthesizes RNA using information encoded along its nucleotide chains. During RNA synthesis, part of the DNA double helix temporarily unwinds and, with the help of enzymes, manufactures a new strand of RNA by aligning along its length freely available nucleotides within the cell aqueous solution. The pattern of DNA nucleotides determines the sequencing of the new RNA molecule, with enzymes assisting in both the positioning and linkage of the nucleotides. When complete, the new RNA molecule is released, with DNA rewinding into a double helix, ready to repeat the process.

Among RNA's roles is the manufacture of enzymes. It does this by linking together individual amino acids into peptide chains in a way not dissimilar to the DNA construction of RNA. Finally, DNA contains the genetic information necessary for its own replication, although once again it depends upon enzymes to carry out the process. During replication, the DNA double helix unwinds completely, producing two separate single polynucleotide strands. With the help of enzymes, free nucleotides within the cell are collected and linked to each of the separate strands, producing the two DNA double helixes required in replication. Hence in the most sophisticated of interdependencies at the core of the life process, DNA manufactures RNA, and RNA manufactures the enzymes on which DNA depends to carry out its various functions.

Another important biochemical function in life is how energy from the outside environment is acquired for use in metabolic activity. There are only two sources of external energy harnessed by all life—sunlight and chemical energy in the form of redox chemical reactions with the surrounding environment. A redox reaction is one involving the transfer of an electron from an "electron donor" such as a metal, to an "electron acceptor" such as oxygen, while in the process releasing a small amount of usable energy. Organisms such as plants that derive their energy from sunlight are called phototrophs, while microorganisms that derive their energy by redox reactions, often with inorganic materials in the environment, are called chemotrophs.

After acquiring energy, all phototrophs and virtually all chemotrophs then activate a sophisticated "electron transfer chain" to move the acquired energy across their cell membranes. While doing so, they also move protons (hydrogen atoms with their single electron removed) from one side of the membrane to the other. This is crucial, because the accumulation of protons across a membrane acts like a small electrical battery, storing the energy harnessed from the outside environment for future use. Subsequently, in what is called a "proton pump," the stored energetic protons release their energy to manufacture the enzyme ATP-synthase, which itself makes adenine triphosphate (ATP), the vital "energy currency" molecule used within all living organisms. Even in organisms where an electron transfer chain is not activated, as in some archean microorganisms, ATP is still manufactured using the energy from protons acquired directly from their immediate environment. Hence at the core of energy production within all life, we find proton pumps used to manufacture ATP-synthase and subsequently ATP.

Echoes of our Origins

Given an origin for planet Earth itself, there must also have been a moment when life first emerged. Whether that involved an actual origin to life on the planet, or its arrival from elsewhere in the Universe during Earth's early history, is currently unknown. Nevertheless, what we have so far learned about the natural history of our planet and the evolution and biochemistry of life provide valuable clues to the first organisms to inhabit our world, and may also help to uncover an actual origin to life here. Within the fabric of life today reside echoes of our origins.

For example, while currently DNA is crucial to virtually all life, its complexity and dependence upon enzymes constitute a highly developed biochemical system, suggesting a precursor means of preserving genetic information and of replication and, hence, a time-line of development in the biochemistry of life. Other biochemical processes suggest similar development over time. Photosynthesis, for example, constitutes a sophisticated mechanism for acquiring energy, suggesting that it too has evolved from precursor methods of acquiring metabolic energy from sunlight. And aerobic respiration—the process of releasing biochemically stored energy in the presence of oxygen—could only have become dominant subsequent to oxygen becoming available in our atmosphere, indicating that anaerobic respiration emerged at a prior stage. Many other examples reveal similar complexities, symbioses, and dependencies that point to an evolution in the structure and biochemical operation of life over time.

Overall, the developmental path in life indicated both by Darwinian evolution and within biochemistry suggests that the first organisms on Earth were simpler in morphology and biochemical operation. Indeed, the fact that all living organisms consists of one or more living cells, and are underpinned by the five basic functions of life outlined above, perhaps points to a minimum requirement for life. For example, fossilized evidence of the earliest known life on Earth, dating back to approximately 3.5 billion years ago, is of microbial life only, while RNA-only viruses and chemotroph microorganisms both point to alternative modus operandi in life separate from the more sophisticated biochemistry associated with DNA and photosynthesis. Such evidence points to the first life on Earth being single-celled entities capable of at least the basic functions of life, and having biochemical properties that were perhaps related to RNA-only viruses and archean chemotrophs found in extreme environments.

Even with such insight into the possible nature of the very first organisms, as stated above, we cannot yet tell whether the first organisms to inhabit our planet originated here, or whether they came from elsewhere in the Universe. Hence, a search for an actual origin to life must include a widespread and thorough investigation of many of the other bodies of the Solar System. Such a search, however arduous, should eventually reveal whether ancient microbial life emerged elsewhere in our Solar System, or perhaps even came from the original nebula from which our Solar System emerged.

If, on the other hand, life originated on Earth itself, clues to its actual origin may be found from our improving grasp of the natural history of our planet and the nature of life. For example, the longstanding connection between life and the environment points to a similarly close coupling between the processes of any origin and Earth's earliest environment. Indeed, given the ever-changing and evolving biosphere, the conditions within which an origin to life occurred would have been very different to those of today. However seemingly toxic by our standards, Earth's earliest environment was conducive to life and could well have brought about its origin. Certainly the discovery of archean extremophile microorganisms at sub-oceanic hydrothermal vents demonstrates that life is possible in the most hostile environments, while chemoautotrophic microorganisms demonstrate that basic life can harness even inorganic materials both for energy and organic nutrients, suggesting that Earth's early and relatively hostile environment could have supported an origin to life.

Hence, we envisage an origin process involving a previous and separate era to life itself—an era of prebiotic chemical evolution, dependent on the prevailing planetary conditions and natural resources, from which emerged single-celled organisms exhibiting at least the basic functions of life, perhaps simpler in biochemical operation yet with a capacity to evolve into ever more capable forms.

The search for origins is reduced to an intricate investigation of our planet's earliest history, to determine the natural resources that were available, the prebiotic chemistry that was possible (and actually occurred), and how it led increasingly toward biochemical systems that isolated themselves from their surroundings in cellular structures and developed the basic essentials of life.

The Origin and Early History of Earth

Five thousand million years ago, our Sun formed within a vast nebulous cloud of gas and dust. The material of the cloud originated inside pervious stars long since deceased and from gases created during the formation of the Universe. Over millions of years the cloud coalesced into a number of slowly rotating clumps. Eventually, our Sun began to take shape from one clump as a dense swirling globe more than a million kilometers across, with its remaining material condensing into a thick rotating disk stretching for billions of kilometers beyond. Pressure at the center became so great as to trigger nuclear fusion, converting hydrogen into helium and releasing vast amounts of energy into space. Our Sun had begun its life as a new star within the immense Milky Way galaxy.

As the surrounding debris coalesced about the Sun, complex chemical and mechanical interactions were triggered by solar energy, cosmic radiation, and electrostatic and magnetic activity within the field itself. Many new materials were synthesized, including volatile and organic materials such as water and carbon dioxide, among others, to at least the complexity of amino acids and nucleic acids. Most of the remaining hydrogen and helium found its way to the outer region of the disk, eventually to become the giant planets Jupiter, Saturn, Uranus, and Neptune. Closer in, the remaining light gases mixed with heavier materials to form dust and ice particles that, over millions of years, accumulated into rocks, boulders, and colossal planetoids, eventually becoming the protoplanets of the inner Solar System.

The emerging planets all jostled and struggled with one another. Chaos ensued as each settled into orbit while enduring cataclysmic collisions with other forming planets as well as relentless bombardments from the millions of planetary remnants. Eventually only four rocky planets survived the battle for the inner Solar System—Mercury, Venus, Earth, and Mars. Each would endure further pounding for millions of years, but they would survive. They had grown to hundreds of times the mass of even the largest remaining planetary invader, and although regularly inflicted with serious surface damage, each planet could by now hold together and maintain its orbit. The inner Solar System as we know it was taking shape.

Having emerged from a single debris field, three of the four inner planets—Venus, Earth, and Mars—may have begun their existence quite similarly. All enjoyed, to various degrees, a soothing heat from the Sun. All three were by now substantial rocky planets, settling in the same broad region of the inner Solar System, and all were quite similar in material composition, internal planetary dynamics, and surface conditions. Significant differences would eventually emerge among the three, but in the beginning they would have been broadly similar.

As Earth grew toward its present size, its overwhelming gravity drew all of its accumulated material into a near-perfect globe. Any mountain too high would crush under its own weight and any rift too deep would fill with debris falling from above. A process of material and chemical differentiation drew heavier materials toward the center of the planet, forcing lighter material toward the surface. The core of the planet became hotter, powered both from the gravitational contraction and radioactive decay of heavy metals. The initial heat may have been sufficient to melt up to 60 percent of the interior of the planet, with the core softening and a magma ocean hundreds of kilometers thick forming around it. Hot molten rock and iron circulated within colossal convection currents moving from the depths of the planet toward the surface, where they cooled and flowed inward once again. An electric-dynamo generated by the molten iron created a planetary magnetic field that extended for thousands of kilometers into space, protecting the surface from harmful solar and cosmic radiation.

Even with such inner turmoil, the surface began to cool and solidify. Convective cycling had quickly dissipated much of the internal energy and sorted the materials of the planet according to their density and chemistry. Silicon and oxygen, comprising most of the surface, solidified and formed a relatively low density crust that floated on the more dense material below, maintaining a coherent surface despite the continuing inner activity. Over time, the inner core solidified, although the outer core has remained molten to the present day. The mantle also mostly solidified, though again the outer asthenosphere has remained soft and malleable, churning through slow convection cycles that take hundreds of millions of years to complete.

In the final stage of differentiation about 4.3 billion years ago, in what is called the Hadean Period, hot volatile gasses were ejected in a process of outgassing via the planet's tectonic rifts and volcanoes. In perhaps only a million years, 80 percent of Earth's original atmosphere was produced, with the oceans appearing shortly thereafter. From a central iron core to the upper atmosphere, the materials of the planet had been separated though a process that we suspect is common to many rocky planets.

Along with silicon and oxygen, the new crust consisted of iron, aluminum, calcium, magnesium, and phosphorus, among other materials, all of which chemically reacted to form minerals. The most common minerals on Earth are silicates—minerals made from both silicon and oxygen—including feldspar and pyrite, which are low in metal content, and basalts, which contain more iron and magnesium. The formation of those early igneous rocks became the foundations upon which further surface activity could occur.

Earth's earliest atmosphere, composed primarily of hydrogen, was quickly lost to space. Subsequently, a more stable atmosphere was created from outgassing and from the condensation reactions of water upon the newly formed igneous rocks, producing an atmosphere of carbon dioxide, nitrogen, methane, ammonia, hydrogen chloride, hydrogen sulfide, and sulfur dioxide. Although toxic when compared to today's atmosphere, that early atmosphere acted as an important stabilizing influence. Carbon dioxide and methane would have brought about a greenhouse effect that helped to raise the surface temperature above the freezing point of water, while the increased surface pressure allowed liquid water to persist on the surface for the first time. And with continuing supplies from the outgassing of steam and from impacting comets, the surface became increasingly dominated by water. Eventually vast oceans covered much of the surface and, from then on, all that happened on Earth would be intimately connected to liquid water.

Toward the Origin of Life

Earth had taken about 100 million years to form, attaining its present size approximately 4.4 billion years ago. Along with the turmoil of its early indigenous activity, the planet endured repeated bombardment from space for hundreds of millions of years, but which rapidly ceased about 3.9 billion years ago. With firm evidence of microorganisms as far back as 3.5 billion years, and tentative evidence that life existed 3.8 billion years ago, it seems that life emerged quite rapidly in Earth's early history.

Hence, in attempting to determine how life emerged, it is to that tumultuous young planet and its immediate space environment that we must turn our attention. We must understand the effect of mass bombardments, the nature of our early Sun and Moon, and the indigenous events, such as tectonic, volcanic, hydrothermal, and water-based activity, the formation of the atmosphere, and the resulting climate. We must also determine the planetary environments that could have led to the synthesis of organic compounds and then to their assembly into ever more complex systems, toward prebiotic chemistry and, finally, life itself.

We must begin by considering the origin of organic materials—whether synthesized in space to arrive on Earth from impacting celestial bodies, or synthesized on Earth itself, and, if so, by what processes. We must also determine how biochemically functional blocks, such as nucleic acids and amino acids, originated. Here also we must address one of the most significant features of the biochemistry—that of chirality. Chirality in living systems refers to an asymmetry in the use of biochemical molecules. For example, each amino acid occurs in nature in two forms called left-handed (L) amino acids and right-handed (D) amino acids. While both are found in equal quantities in nature, living organisms use mostly L-amino acids, indicating a required mechanism that either preferentially *synthesized* L-amino acids or preferentially *selected* L-amino acids during the origin of life.

Next we must determine possible methods of energy transductance within the first biochemical systems. The processes leading toward life could not have occurred in an unchanging or stagnant environment. Rather, they must have arisen in an environment of thermodynamic disequilibrium (that is, an environment whose thermal and material characteristics were in flux) and capable of providing energy of a type useful to chemistry and ultimately for metabolic activity while simultaneously providing meta-stable (temporarily stable) conditions that allowed for organization and complexity in form and function to emerge.

Also of importance is how such energy mechanisms became coupled to polymerization chemistry and specifically how the polymerization of nucleic acids into polynucleotides and amino acids into proteins occurred. Here many fundamental issues arise due to the complexity within genetic and protein materials, and their interaction among one another. There is general consensus that such complexity could not have emerged in nature all at once, but was the outcome of a chemical evolution over many stages. Here, several scenarios present themselves. In one, polynucleotides capable of retaining genetic information may have arisen first, subsequently aiding the polymerization of amino acids into proteins akin to how RNA synthesizes proteins in life today. Alternatively, proteins and organic membranes could have emerged first, providing cell-like environments within which concentrated solutions of nucleic acids could then polymerize.

While far from certain, many think it less likely that protein could arise in nature without genetic assistance and that it is more likely that genetic polymers would have arisen first, subsequently aiding the emergence of proteins and cellular membranes. Indeed, many now think that the emergence of RNA in particular was a pivotal event in the origin of life; and that, for a time in Earth's early history, all life may have been based on RNA (or some other related genetic polymer) rather than DNA. Certainly the dependence of DNA on enzymes makes it difficult to see how DNA could have emerged first and have been capable of self-replication before the emergence of proteins and enzymes. Similarly, it is difficult to see how proteins could have arisen without genetic assistance. RNA, on the other hand, has been identified in the laboratory as being capable of self-replicating, while, as already mentioned, RNA-only viruses show that it is possible to have life that is independent of DNA.

Although tentative, such a scenario at least offers a starting point for further investigation. If we accept that life originated in nature, then some sequence of events currently unknown to us led to its emergence and we now consider the emergence of RNA to have been important in this stage.

Possible Pathways—Organic Synthesis

There are two broad scenarios for the origin of organic material. As discussed in Chapter 1, organic synthesis would have occurred throughout the nebula from which Earth formed. We know this because we can currently observe organic synthesis taking place throughout vast molecular clouds between the stars, deep within star-forming nebulae, and within the flattened disks surrounding newly formed stars. Furthermore, evidence from a particular class of meteorites called carbonaceous chondrites, which formed during the origin of the Solar System, reveals a number of organic materials to the complexity of amino acids.

Several astronomical studies have even provided new insights into the issue of chirality. First, a particular meteorite called the Murchison Meteorite (discovered in Murchison, Australia, in 1969) not only contains amino acids but also shows an excess of L-amino acids, indicating a celestial process that originally synthesized more left-handed amino acids within the original solar nebula. Furthermore, recent observations of a region of the Orion nebula, called OMC1, even suggest a possible process—that of circularly polarized light from nearby stars bathing the region and preferentially triggering the formation of L-amino acids. If such mechanisms occurred within the original solar nebula, it is plausible that organic material suitable to life could have been delivered to the surface of our planet during its early history.

A second scenario considers organic synthesis having taken place on the surface of the planet itself. Here, several different mechanisms are envisaged. One mechanism, demonstrated in a famous experiment by Miller and Urey in the 1950s, leads to the production of organic compounds when volatile gases such as carbon dioxide, methane, and ammonia are energized by solar radiation or lightning discharges. In was realized in the 1980s, however, that methane and ammonia in particular would not have remained in Earth's early atmosphere long enough to produce significant quantities of organic material, casting doubt over the validity of this process. More recent studies have shown, however, that even without gases such as methane and ammonia, substantial organic synthesis can occur within a carbon-dioxide-rich atmosphere in the absence of oxygen, indicating that Earth's early atmosphere would have been conducive to organic synthesis.

An alternative and potentially significant source of organic synthesis has presented itself with the discovery of hydrothermal vents on the ocean floor. Hydrothermal systems arise when volcanic materials solidify on or near the surface and then cool, contract, and crack. Any water that circulates through the cracks heats up and flows more rapidly over the newly formed igneous rocks, releasing hydrogen gas which then reacts with carbon dioxide in the atmosphere to produce a range of simple organic materials. Given the favorable conditions during Earth's early history—a carbon-dioxide-rich atmosphere, planetary oceans, and widespread tectonic and volcanic activity—hydrothermal systems may have been an important contributing factor to the supply of organic material, as well as a range of other life-related activity.

Possible Pathways—Polymers and Membranes

The synthesis of organic compounds, even to the complexity of amino and nucleic acids, represented but the first of many steps toward the origin of life. Even the smallest single-celled organism contains more than 100 billion atoms organized in extraordinarily sophisticated ways. Nevertheless, numerous plausible mechanisms for the polymerization of amino and nucleic acids, and for the emergence of cellular–like structures, are now postulated and are the subject of intense and ongoing investigation.

In one scenario, polymerization of nucleic acids into genetic polynucleotides could have occurred with the aid of particular mineral clays found in sedimentary basins, dried lakes, and retreating coastlines during periods of warming climate, or from dry-heat at volcanic settings. For example, in one experiment conducted by James P. Ferris of the Rensselaer Polytechnic Institute, the mineral-clay montmorillonite (hydrated aluminum silicate) was shown to catalyze the synthesis of RNA oligomers (partial polymers). Composed of regular charged layers of aluminum and silicate, montmorillonite can catalyze the production of RNA oligomers by aligning and linking individual sections (called monomers) between adjacent sheets, holding them in place by electric charge. Although far from revealing how RNA emerged in nature, this experiment at least demonstrates a possible process leading toward basic genetic polynucleotides that are capable of catalyzing their own replication. Hence, it is speculated that through such a "naked-genes" scenario, the rise of RNA in nature may have been supported initially by minerals, and that this subsequently brought about the synthesis of organic membranes.

Another scenario considers Earth's early organic-rich oceans giving rise in the first instance to membranes and cellular-like entities, which subsequently facilitated the chemical evolution of genetic polymers. For example, when surrounded by water, many organic compounds, such as amino acids and proteins, coalesce into microscopic spherical structures called coacervates. These organic-rich colloids even allow other organic materials from the surrounding medium to enter, suggesting that coacervates may have provided the first isolated environments within which complex prebiotic chemistry occurred.

Yet another scenario considers hydrothermal systems as a possible seat for the origin of life. As originally considered by Gunter Wachterschauser in the 1980s, and subsequently by many others, life may have emerged within black smoker hydrothermal vents on the ocean floor. In such settings, tiny caverns coated with iron sulfide (pyrite) inorganic membranes could have acted as micro-environments within which life's first steps began. The hydrothermal vent itself could have provided both organic raw material and chemical energy; while within each tiny cavern, polymerization of nucleic acids toward RNA could have been supported by the unique geometry of pyrite crystals, which are now considered to be capable of catalyzing such reactions. Subsequently, synthesized lipids and proteins could have gradually replaced the inorganic iron sulfide membranes, leading increasingly toward organic-based cellular entities. Given such a range of intriguing possibilities, many now regard hydrothermal systems as a serious contender for the origin of life.

However rudimentary, all current scenarios point to a geochemical context for the origin of life, with mineral rocks and clays potentially as significant as organic synthesis and the presence of water. Indeed, minerals could have performed numerous important roles during the origin of life. First, they could have acted as containers and scaffolds—as with montmorillonite—supporting and aligning organic monomers and enabling polymerization. They could also have acted as templates for particular reactions and perhaps even offered a planetary context to the chirality issue. For example, in experiments by Robert Hazen, Timothy Filley, and Glenn Goodfriend in 2001, crystals of calcite immersed in a solution of both left- and right-handed amino acids were coated with a surface layer of mostly L-amino acids *and* also assisted in their polymerization, representing a plausible geochemical mechanism for the production of protein from L-amino acids on the young Earth. Minerals could also have acted as catalysts, providing an intermediary role in organic synthesis—as in the example above, where dissolved iron sulfide may have provided the initial framework for the formation of membranes and for genetic polymerization in sub-aqueous hydrothermal vents. Finally, inorganic minerals, which participate in the biochemistry of life today, could equally have been involved in the chemistry of life from the beginning. Overall, a geochemical context for the origin of life is now recognized, through which otherwise impossible chemical processes relevant to the origin of life may have been enabled.

A Way Forward

Uncovering the origin of life on Earth may seem to be an enormous if not insurmountable task. But if our origin has a basis in nature, there is no better means at our disposal than the relentlessness of modern science to uncover the processes involved. Nevertheless, it is unlikely that we will discover a singular piece of evidence that quickly and resolutely reveals "the origin of life." Rather, we now recognize that the search for origins is a process of elimination and refinement through experimentation and exploration, leading us to ever more elusive yet vital clues that will gradually improve our understanding of the processes involved.

As shown throughout these opening chapters, we have already made an excellent start—identifying an ancient and planetary context for the emergence of life, realizing the likely nature of the first organisms, and even identifying a range of possible scenarios through which the steps toward life may have occurred. But it is just a start. We cannot yet even conclude that life actually originated on Earth. For this we must obtain a statistically significant sample set from across the entire Solar System that conclusively reveals either the presence or absence of microbial life elsewhere in the early Solar System. And while we pursue that agenda, it is also prudent to consider an origin of life on Earth itself, arguably as good a place as any for life to have originated. In this we must continue with our in-depth investigations into the many contributing factors on our planet and in its immediate vicinity in space. We must determine the organic synthesis that occurred within the original solar nebula, as well as the precise stocks of volatile and organic materials that were delivered to the planet's surface through mass bombardment. We must comprehensively understand Earth's earliest intrinsic tectonic, volcanic, and hydrothermal systems, its early atmospheric composition, and the character of its early water systems—their acidity, redox potential, water activity and salinity, and so on. The greatest challenge, however, will be in determining the actual environmental settings in which organic synthesis, polymerization, and other complex prebiotic chemistry could have led toward the first single-celled organisms.

While the search for the origin of life will always be pursued on Earth, the discovery of new evidence can be extraordinarily difficult. In perhaps the greatest of ironies, the relentless evolution of, and ancient link between, our planet and life itself means that virtually no trace of Earth's earliest history persists (although ever-improving techniques allows for ever more elusive evidence to be uncovered). But given the significant planetary context for origins, an important new opportunity now presents itself with the planet Mars. With broadly similar early histories, many of the external and intrinsic planetary factors contributing to the origin of life on Earth may also have affected Mars. From our robotic Mars missions to date we can already see that, unlike on Earth, Mars actually retains a substantial record of activity from its earliest history, presenting a significant new avenue for directly probing planetary and Solar System activity from that era. Indeed, such is the mass of evidence awaiting us and such are the gaps in our knowledge, that Mars may well provide significant new insights into Earth's early history and the origin of life. In both challenging our current ideas and in stimulating brand new thinking, Mars can provide opportunities that are simply not available on Earth, enhancing our understanding of the circumstances through which life originated. And if, as we now think plausible, life actually emerged in Mars' early history, that planet may even provide far-reaching answers both on the origin of life and its broader, cosmological context.

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