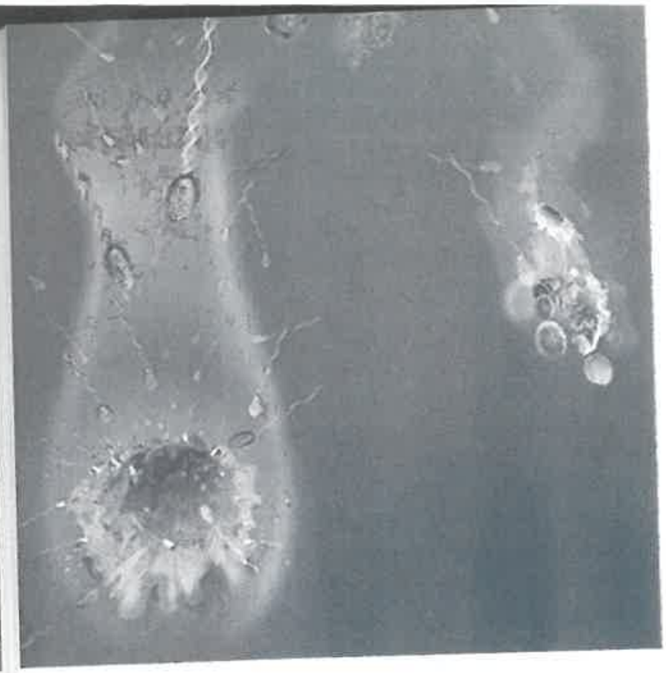


CHAPTER 10

Origin of Earth and of Life

Key Questions

- How old is Earth?
- How did the solar system form?
- How did the atmosphere and ocean form?
- What was the composition of the atmosphere early in Earth's history?
- When and how did life originate?
- Why did the earliest organisms show a preference for hot environments?

Chapter Overview

Earth formed some 4.6 billion years (b.y.) ago by the accretion of solid particles from a cloud of gas and dust surrounding the young Sun. Earth's atmosphere and ocean started forming as the planet itself was being built as a consequence of the release of volatile materials during impacts. The atmosphere and ocean continued to grow during the so-called heavy bombardment period between 4.6 and 3.8 b.y. ago, although new evidence suggests that the bombardment may have been a pulse, rather than an ongoing process. The composition of the atmosphere is unknown because little or no rock record survives from that time, but it probably consisted mostly of N_2 and CO_2. Life may have originated during the heavy bombardment period from reactions between organic chemicals created in Earth's surface environment or imported from space. This may explain why the last common ancestor of all extant life appears to have come from a hot environment.

INTRODUCTION

Earth is a smallish planet that orbits an ordinary star, our Sun. Earth is special, however, because it is the only planet in the universe that is known to harbor life. How was Earth formed, and how did it come to be habitable? These are questions we need to understand if we are to assess the possibility that life might exist elsewhere. We must also try to understand how life itself originated. Was it a chance occurrence, or was it a phenomenon that was almost unavoidable on a young, habitable planet like Earth? We don't know the answers to these questions yet, but scientists have made progress over the last few decades in determining how both our planet and ourselves came to exist.

Introduction to Geologic Time

One of the most important points that any geology professor makes to an introductory class is the immense amount of time represented in the geologic record. For reasons outlined below, scientists believe that Earth and the rest of the solar system formed about 4.6 b.y. ago. (See box titled "A Closer Look: Determining the Age of Earth.") The universe itself has existed for roughly 14 billion years, based on estimates of its current rate of expansion. Both the age of Earth and the age of the universe are almost inconceivably longer than a typical human lifetime of about 80 years or even the total amount of time that humanlike species have been in existence, about

A CLOSER LOOK

Determining the Age of Earth

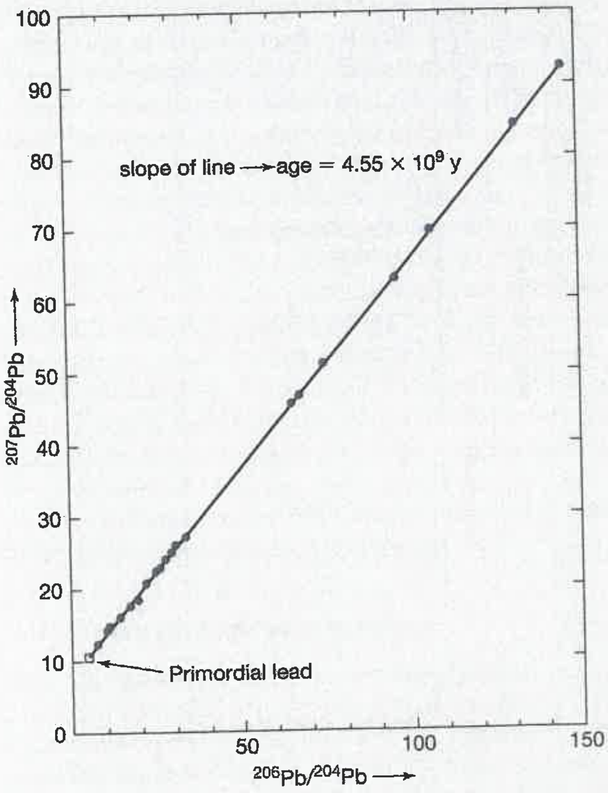
The problem of determining Earth's age is somewhat complicated even though the basic principles of radiometric dating (Chapters 5 and 7) are straightforward . The reason is that standard parent–daughter age-dating techniques, like the uranium–lead system, yield only the crystallization ages of the minerals to which they are applied, not the age of the material itself. But, as far as geologists know, none of the rocks and minerals that composed Earth's original crust have been preserved. The oldest minerals that can be dated by standard techniques are a handful of **zircons** (a zirconium silicate mineral) that yield ages of up to 4.4 b.y. How do we deduce that Earth is actually about 150 million years older than this?

To find Earth's age, one must first answer a related question: How old are meteorites? **Meteorites** are pieces of rock and/or metal that are thought to have drifted around the solar system for billions of years before hitting Earth. They have been collected from all over the planet but are found most readily in Antarctica, where they are easily spotted on the ice. The gradual flow and melting of the ice concentrates meteorites in a few specific localities, making them especially easy to find. The most primitive meteorites (because they have not been altered by melting) are called **chondrites**. Dating of chondrites provides an upper limit on Earth's age because these objects are thought to have formed at the same time as the solar system as a whole.

Meteorites can be dated using standard parent–daughter techniques, but the most accurate method—**lead–lead dating**—involves the use of multiple lead isotopes. The reason this is useful is that the U/Pb ratio differs from one meteorite to another and even among different minerals within the same meteorite, so it is difficult to determine what the initial U/Pb ratio must have been. By using multiple isotopes, we can avoid this problem. The three isotopes used are ^{204}Pb, ^{206}Pb, and ^{207}Pb. The lead isotopes ^{206}Pb and ^{207}Pb are radiogenic isotopes that derive, respectively, from the decay of ^{238}U and ^{235}U. The half-lives of these decay processes are 4.5 b.y. and 0.713 b.y. The third lead isotope, ^{204}Pb, is a nonradiogenic isotope that is used for comparison in the measurements. By measuring the abundances of these isotopes in different meteorites and then plotting the ^{206}Pb/^{204}Pb ratio on one axis and the ^{207}Pb/^{204}Pb ratio on the other, we can construct what is known as an **isochron diagram** (Box Figure 10-1). If all the samples being analyzed have the same age, as is true for chondritic meteorites, then the data should (and do) all fall on a straight line. The slope of this line tells us the age of the collection of meteorites, which is accurately determined as 4.55 b.y.

Moon rocks, which were brought back by the *Apollo* spacecraft missions of the late 1960s and early 1970s, can be dated in a similar manner. The oldest Moon rocks are about 4.44 b.y. old, suggesting that the Moon formed soon after the solar system itself. The Moon could be even older than this, as there is no guarantee that we have found the oldest Moon rock.

Earth's age is more difficult to obtain because the oldest rocks are all gone. They were probably recycled back into the interior by plate tectonics. However, Earth's age can be deduced indirectly by examining lead isotope ratios in rocks containing lead minerals, that is, minerals that initially contained lead, but little or no uranium. (U–Pb dating, in contrast, is performed on minerals that initially contained uranium, but little or no lead.) The isotopic composition of lead minerals is the same as that of the magma from which they formed. Because Earth's mantle contains uranium as well as lead, the abundances of ^{206}Pb and ^{207}Pb in the mantle have increased with time, as have those of the magmas derived from it. If we plot the lead isotope ratios from rocks of different ages and then analyze the resulting curve mathematically, we can show that, 4.5 to 4.6 b.y. ago, Earth's mantle should have had the same ^{206}Pb/^{207}Pb ratio as meteorites. This, in turn, implies that Earth formed at the same time as the rest of the solar system, about 4.55 b.y. ago. This radiometric age scale is the fundamental underpinning to most of our theories about how Earth formed and evolved.



BOX FIGURE 10-1 An isochron diagram, showing lead isotope ratios from a collection of chondritic meteorites. The fact that all the data fall on a straight line shows that all the meteorites have the same age. The age of the meteorites, 4.55 b.y., is determined from the slope of the line. (*Source:* From K. K. Turekian, *Global Environmental Change: Past, Present, and Future*, 1996. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

4 million years (m.y.). An analogy that is sometimes made is to scale down Earth's age to a single calendar year beginning at 12:01 A.M. on January 1. In that case humans would have first appeared at about 4:40 P.M. on December 31, and the oldest human (about 120 years) would have been born less than one second before midnight later that evening.

In Chapter 1, we introduced the geologic time scale and discussed two events, the Pleistocene glaciations and the K–T mass extinctions, that occurred relatively recently in Earth history. In this chapter, we focus on events that occurred billions of years ago. The major **eons** into which geologic time is divided are the Hadean (4.6–3.8 b.y. ago), Archean (3.8–2.5 b.y. ago), Proterozoic (2.5–0.54 b.y. ago), and Phanerozoic (0.54 b.y. ago–present). The first three of these time intervals are often collectively termed the Precambrian because they come before the Cambrian period, when **shelly fossils** (fossilized remains of shelled organisms) became abundant in the rock record. Figure 10-1 shows some of the other major events that have occurred during Earth's history.

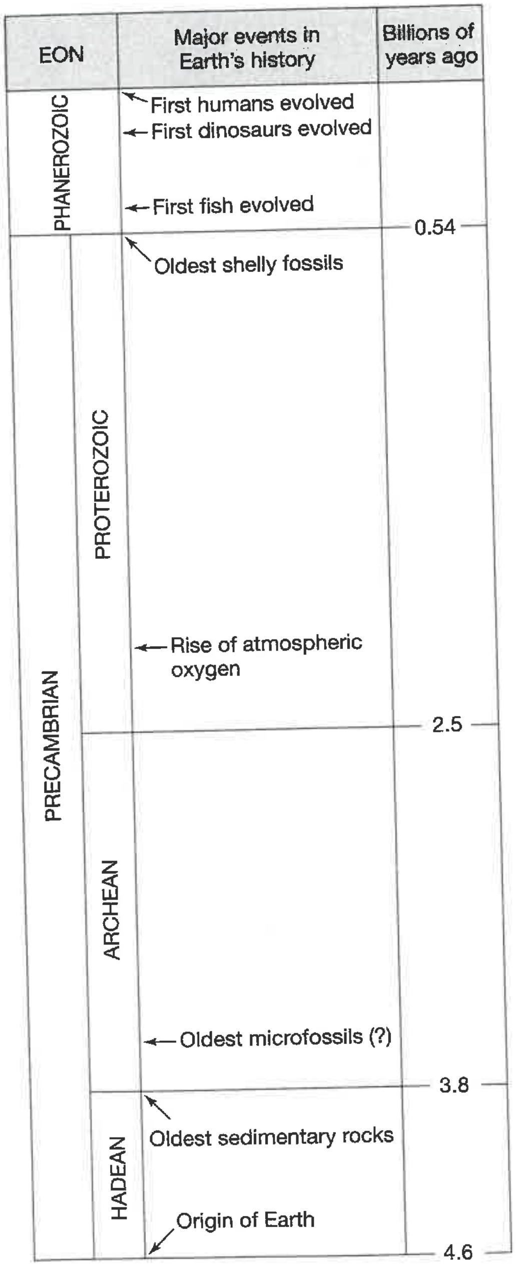


FIGURE 10-1 The geologic time scale, showing major events in Earth's history. (*Source:* From R. W. Christopherson, *Geosystems: An Introduction to Physical Geography,* 3/e, 1997. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

FORMATION OF THE SOLAR SYSTEM

How did Earth and the rest of the solar system form? This question has fascinated astronomers for hundreds of years. It is interesting to Earth system scientists as well because it sets the boundary conditions for the rest of Earth's subsequent evolution.

Formation of the Solar Nebula

The Sun is thought to have formed from a collapsing cloud of interstellar dust and gas. Such **interstellar clouds** are observed today by both optical and radio telescopes (Figure 10-2). The one shown in Figure 10-2 is a particularly spectacular one that happens to be backlit by some bright blue stars. It is a portion of the Eagle Nebula, which is sometimes referred to as the "Pillars of Creation." Interstellar clouds are concentrated in the spiral arms of our Milky Way galaxy, where the density of material is highest. If such a cloud is dense enough and cold enough (about 10 K), it will collapse under its own self-gravity and the process of star formation can begin. It may seem counterintuitive that a cold cloud is required to form a hot star, but this is indeed the case. The reason is that, according to the ideal gas law (Chapter 4), a cold gas exerts less pressure than a warm gas of the same density. A cold interstellar cloud has less internal pressure to counteract the force of

FIGURE 10-2 [See color section] The Eagle Nebula viewed from the Hubble Space Telescope. (*Source:* NASA Headquarters.)

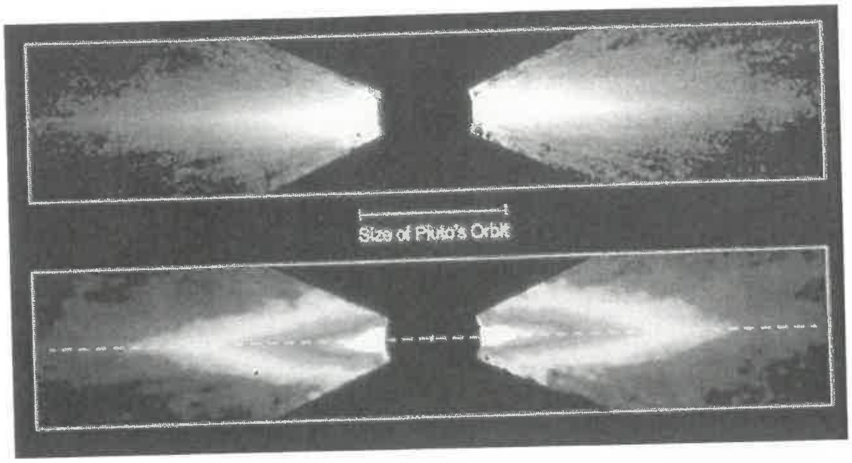


FIGURE 10-3 [See color section] The disk around the star Beta Pictoris, as seen from the Hubble Space Telescope. Top panel: Visible light image. Bottom panel: False color image created by image processing to highlight features in the disk structure. (*Source:* NASA Headquarters.)

gravity and is therefore more likely to collapse. Once it does so, the cloud immediately warms up because the infall of material releases gravitational energy, which is converted into heat. The innermost part of the cloud eventually becomes hot enough for thermonuclear fusion reactions to begin, and a new star is born.

The clouds that are observed in interstellar space are typically many thousands of times the mass of the Sun. As they contract, however, they produce smaller fragments that can themselves contract to form one or more stars. Whether the collapse results in a single star, or a multiple star system, depends largely on how fast the cloud fragment is rotating: the faster it rotates, the more likely it is to form two or more stars. In the case of our own Sun, a single star formed. This is fortunate for us, because a multiple star system would probably be a very difficult place to form a habitable planet like Earth. (It is difficult to identify stable orbits in such systems and probably even more difficult to form a planet in just the right place.) The cloud fragment did have a certain amount of rotation, however, and this caused some of its material to spread out into a disk. The gas and dust that made up the disk are referred to as the **solar nebula**. Astronomers have now been able to see similar disks around other Sun-like stars. Figure 10-3 shows the disk around the star Beta Pictoris, which was the first such disk to be discovered.

Formation of Planets

Once the solar nebula was in place, the process of planetary formation would have begun. The nebula itself would have been heated by the emerging Sun—the **proto-Sun**—so its interior would have warmed. At the same time, small particles of solid material would have begun to condense from the gas. In the hot, inner parts of the nebula, these grains consisted mainly of rocky materials such as iron and silicate minerals that can condense at temperatures as high as 2000 K. That is why Earth and the other **terrestrial planets** (Mercury, Venus, and Mars) are composed principally of rock. In the cooler, outer parts of the nebula, icy materials such as water (H_2O), methane (CH_4), and ammonia (NH_3) would also have condensed. Thus, the giant planets (Jupiter, Saturn, Uranus, and Neptune) contain large amounts of these more volatile compounds. **Volatile compounds** are substances that have low boiling points. The particles formed by condensation were gravitationally attracted to the mid-plane of the nebula, where they clumped together to form **planetesimals**, small protoplanets. These planetesimals collided with each other, often sticking together to form larger bodies in a process called **accretion**. This process is shown schematically in Figure 10-4. Over tens to hundreds of million of years, the planetesimals grew to form the planets that we see today.

While Earth was growing by accretion, its core should have started to form. Recall that the innermost parts of Earth are its solid inner core and liquid outer core, both composed mainly of iron and nickel. Core formation was once thought to have been triggered by radioactive heating after Earth was fully formed. But it is now believed that core formation occurred as the planet itself was forming. Some of the planetesimals that collided with Earth during accretion were so large that they melted large portions of the crust and upper mantle. This allowed the iron and nickel to separate out and flow down to form the core.

Formation of Jupiter

Two specific events that occurred during the process of planetary accretion have special significance for surface conditions on Earth. The first was the formation of the giant planet Jupiter. Jupiter has over 300 times the mass of Earth and more than three times the mass of the next largest planet, Saturn. The reason Jupiter is so large, astronomers believe, is that its core accreted early enough to capture large amounts of hydrogen and helium from the solar nebula before the nebula dissipated. Accretion would have been rapid at Jupiter's orbit because volatiles could condense in addition to metal and silicates. To capture

(a) A slowly rotating portion of a large nebula becomes a distinct globule as a mostly gaseous cloud collapses by gravitational attraction.

(b) Rotation of the cloud prevents collapse of the equatorial disk while a dense central mass forms.

(c) A protostar "ignites" and warms the inner part of the nebula, possibly vaporizating preexisting dust. As the nebula cools, condensation produces solid grains that settle to the central plane of the nebula.

(d) The dusty nebula clears by dust aggregation into planetesimals or by ejection during a T-Tauri stage of the star's evolution. A star and a system of cold bodies remains. Gravitational accretion of these small bodies leads to the development of a small number of major planets.

FIGURE 10-4 The process of planetary accretion. By colliding with each other, (a) small planetesimals (b) grow gradually into (c) large planets. (*Source:* From W. K. Hamblin and E. H. Christiansen, *Earth's Dynamic Systems*, 8/e, 1998. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

hydrogen efficiently, Jupiter's core must have grown rapidly to a mass several times that of Earth. Observations of young stars indicate that nebular gas and dust persist for at most a few million years, after which time they are either incorporated into planets or they spiral back into the star.

Jupiter affects surface conditions on Earth by perturbing asteroids from the asteroid belt into Earth-crossing orbits and by preventing most comets from reaching the inner solar system. The first effect makes Earth a more dangerous place to live, whereas the second one tends to make it safer. As mentioned in Chapter 1, impacts of comets and asteroids are thought to have played a major role in the evolution of life. A large asteroid impact may have caused the extinction of the dinosaurs, and this may in turn have paved the way for the rise of mammals. Thus, biological evolution might have taken an entirely different course had Jupiter not attained the size that it did.

Formation of the Moon

Another celestial event that had a profound influence on Earth's subsequent evolution was the formation of the Moon. Most of us know that the Moon's gravitational pull affects ocean tides. However, few people are aware that the Moon affects climate as well. It does so by stabilizing Earth's obliquity. Recall from Chapter 4 that it is Earth's *obliquity,* or tilt (currently 23.5°), that gives rise to the normal progression of the seasons at middle to high latitudes. We will see in Chapter 14 that Earth's obliquity varies slightly and that these variations have influenced the glacial–interglacial cycles of the past 3 million years. Computer modeling studies have shown that, without the Moon, Earth's obliquity would vary by much larger amounts, occasionally reaching values as high as 85°. This would wreak havoc with climate because the seasonal cycles would be extremely large over much of Earth's surface. Thus, from the standpoint of planetary habitability, the formation of the Moon may be one of the most important events to occur during the formation of the solar system.

How exactly did it happen? Many theories have been advanced, including co-accretion (accreting in Earth's orbit at the same time as did Earth), fission (splitting apart of a rapidly rotating Earth), and capture (gravitational capture of a body that originated elsewhere in the solar system). Most of these theories, however, involve steps that are either physically implausible or that would produce a lunar composition different from that observed in Moon rocks. From the samples collected by the *Apollo* astronauts, we know that the Moon is depleted in volatile elements compared to the bulk Earth and that its oxygen isotopic composition is similar to that of Earth's mantle. Its density is substantially lower than that of Earth, indicating

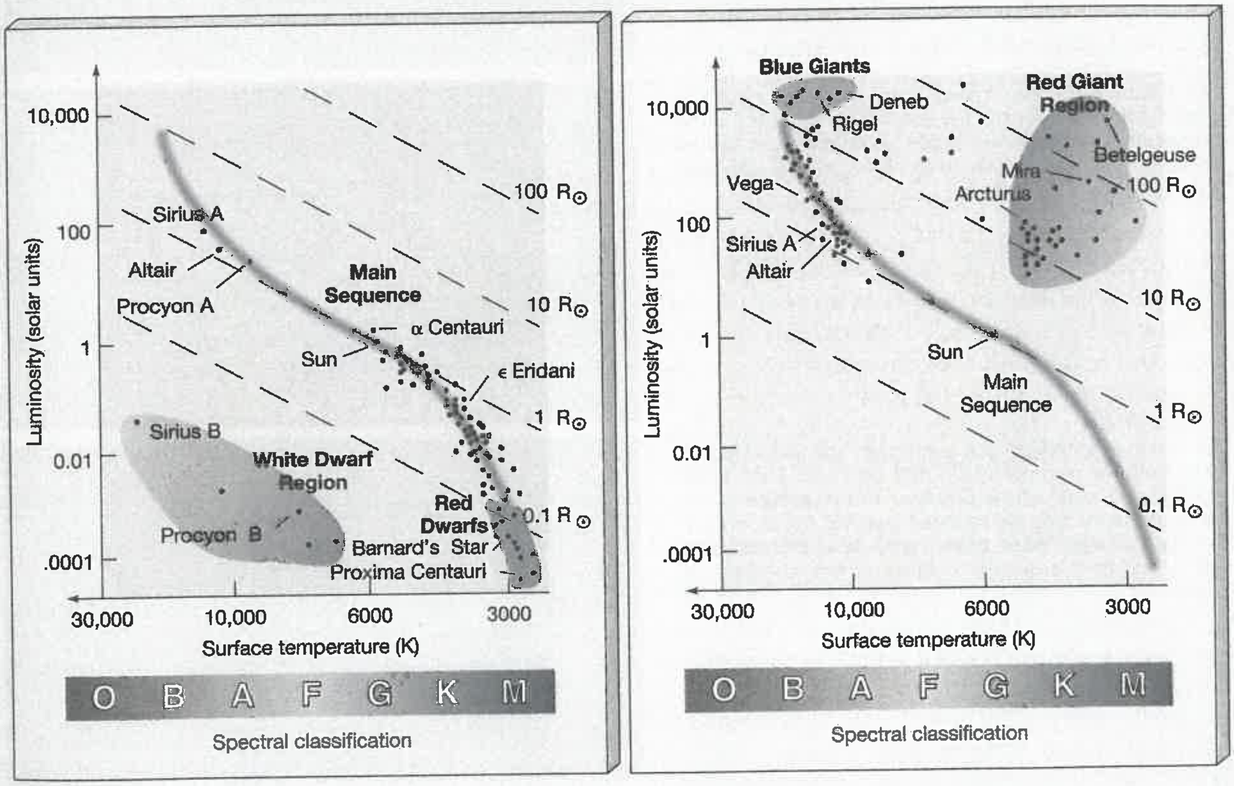
A CLOSER LOOK

Main-Sequence Stars and the Hertzsprung–Russell Diagram

The **Hertzsprung–Russell (H–R) diagram** is a standard means of categorizing different types of stars (Box Figure 10-2). The horizontal axis represents the effective radiating temperature of the star, as determined by Wien's law (Chapter 3) or by some equivalent method of analyzing the star's spectrum. For historical reasons, temperature is always shown increasing to the left. The vertical axis represents the luminosity of the star relative to that of the Sun.

As Box Figure 10-2 shows, most stars fall along a well-defined band that runs from the upper left of the diagram to the lower right. This band is referred to as the **main sequence**. It consists of "normal" stars—that is, stars that are in the slowly evolving, middle phase of their existence. Stars are further grouped into seven classes on the basis of their spectra as O, B, A, F, G, K, or M. The brightest, bluest, and most massive (O and B) stars are referred to as early-type stars; the dimmest, reddest, and least massive (K and M) stars are called late-type stars. Within these categories, stars are further assigned numbers ranging from 0 (early) to 9 (late).

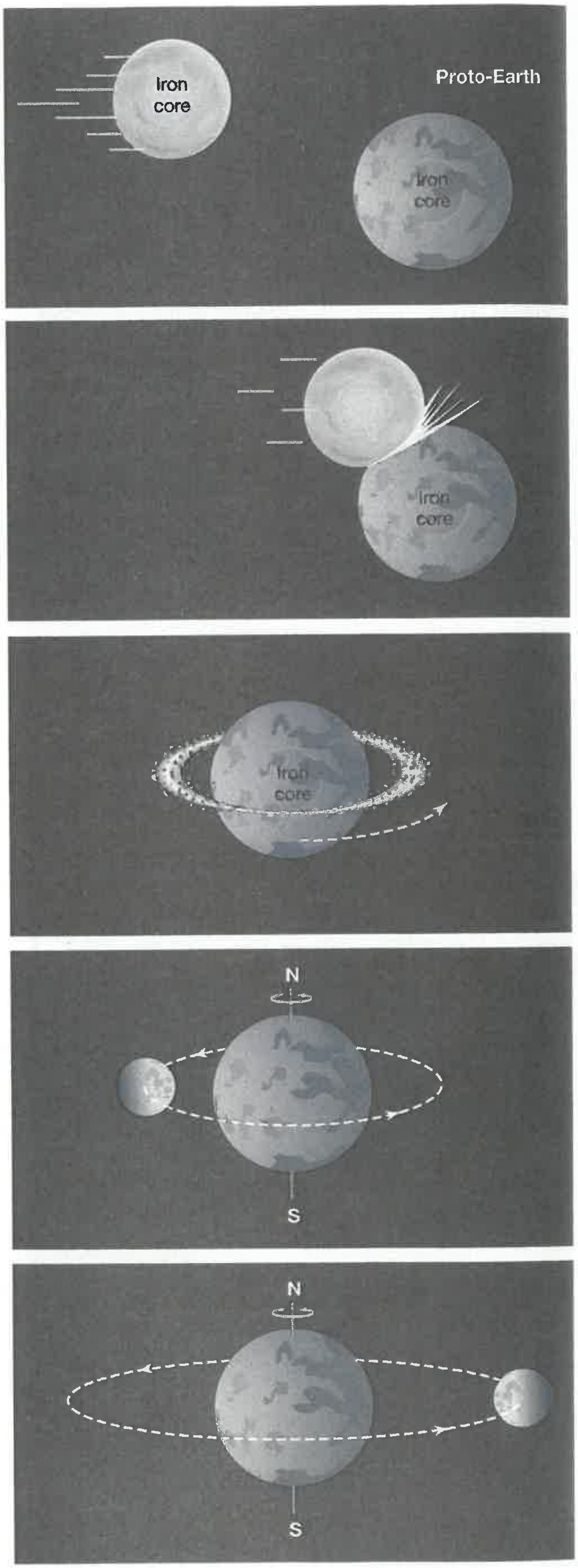
Our Sun is an unremarkable G2 star that occupies a spot near the middle of the main sequence. In about 5 b.y., the Sun will evolve off the main sequence and become first a red giant (at the upper right in the H–R diagram) and eventually a white dwarf (at the lower left). The Sun is drifting slightly upward on the H–R diagram during its main-sequence lifetime as a consequence of the conversion of hydrogen to helium. This effect is small compared with the changes that occur before and afterward, but it has important effects on planetary climates. It is this slow, main sequence evolution that gives rise to the faint young Sun paradox and that may limit the lifetime of Earth's biota in the future.



BOX FIGURE 10-2 [See color section] Hertzsprung–Russell diagram showing different classes of stars. (*Source:* From E. Chaisson and S. McMillan, *Astronomy: A Beginner's Guide to the Universe,* 2/e, 1998. Reprinted by permission of Prentice Hall, Upper Saddle River, N.J.)

that the Moon is also depleted in iron. Furthermore, the Moon appears to have had a completely molten surface, or **magma ocean**, shortly after it formed.

One theory that is consistent with all of the available evidence is the **giant impact hypothesis** (Figure 10-5). According to this hypothesis, Earth received a glancing blow from a Mars-sized planetesimal during the latter stages of accretion, and the debris from the impact reassembled in orbit around Earth to form the Moon. This type of cosmic accident is statistically unlikely, but not so unlikely as to be implausible. We know that it is not a commonplace occurrence because none of the other terrestrial planets have large moons. (Mars has two tiny moons, Phobos and Deimos, but these are thought to be captured asteroids.) Current models



A) A Mars-sized body, 0.1 to 0.2 Earth masses, approaches the proto-Earth at an oblique angle.

B) The two bodies collide. The ejecta from the impact fly off at an angle and the proto-Earth starts spinning rapidly.

C) The ejecta from the impact form a disk around the proto-Earth. The debris in the disk collide with each other and accrete to form the Moon. The iron core of the impactor collides again with the proto-Earth and becomes part of its core.

D) The Moon is initially only a few Earth radii (~20,000 km) away from the now nearly fully-formed Earth. Earth spins rapidly as a result of the collision. The daylength is 5-6 hours. Because they are so close together, the Moon and the Earth generate huge tides in each other that dissipate energy and transfer angular momentum from the Earth to the Moon.

E) Over time, Earth's rotation slows, while the Moon retreats to its present orbital distance of ~60 Earth radii (384,400 km). The Moon's current rate of recession is ~1 cm/yr.

FIGURE 10-5 Schematic diagram illustrating the formation of the Moon by a giant impact.

of accretion suggest that giant impacts themselves should occur fairly frequently, but that most would not have the right geometry to form a large moon. Our own Moon resulted from one giant impact that did, which is fortunate for us, because the Moon has made Earth's climate much more stable than it might otherwise have been.

FORMATION OF THE ATMOSPHERE AND OCEAN

Even after Earth had recovered from the effects of the Moon-forming impact, its surface would still have been an active and hostile environment. Continued bombardment of the surface by smaller planetesimals should have released large amounts of water and other volatile compounds directly into the atmosphere. This phenomenon is referred to as **impact degassing**. The process has been studied in the laboratory by firing high-speed bullets into targets of volatile-compound–rich material, such as carbonate rock. The shock from the bullet's impact causes the carbonate rock to release gaseous CO_2. Similar shock-induced degassing should occur when volatile-compound–rich planetesimals from the asteroid belt region or from the outer solar system collided with Earth's surface.

The energy released by the impacts, combined with the greenhouse effect of the gases given off, may have kept Earth's surface so hot that all the water would have remained in the atmosphere as steam. Alternatively, Earth's oceans may have periodically condensed and been re-evaporated many times by impacts. Any incoming object larger than about 450 km in diameter would have had sufficient energy to evaporate today's oceans. In either case, both the atmosphere and the ocean should have begun forming as the planet itself formed. This modern conception of planetary formation contrasts with older theories in which Earth was thought to have accreted as a cold, airless body, and in which the atmosphere was thought to have formed later from gases given off by volcanos. Volcanos undoubtedly contributed material to the surface, but the bulk of the atmosphere and ocean were probably formed directly by impacts.

The main period of accretion is believed to have lasted for only about 100 million years. After this time, Earth's surface would have become somewhat more quiescent. Big impacts probably continued to occur sporadically, however, until about 3.8 b.y. ago. The evidence for this **heavy bombardment period** comes from the Moon, Mars, and Mercury. All three bodies appear to have been heavily cratered during their early histories. (Venus does not provide a record of this period because, like Earth, during its history it has been resurfaced many times by volcanism.) The lunar cratering record is the best understood because some of the craters have been dated by using rocks collected near their rims. If the Moon and the other terrestrial planets were being pelted by large objects, it is almost certain that Earth was getting hit, too. The bombardment may have made it difficult for life to have originated before about 4 to 4.2 b.y. ago. We will return to this issue later in the chapter. It may also have brought additional water and other volatile compounds to Earth, particularly if the impactors were comets or volatile-compound–rich asteroids from the outer asteroid belt. So, the atmosphere and oceans may have continued to grow throughout this period.

Over the last few years, the story just told about the heavy bombardment period has come into question. Scientists have known since the days of the NASA *Apollo* manned lunar missions (1969–1973) that many of the Moon rocks are about 3.8–3.9 b.y. old. This was initially interpreted as a pulse of impacting bodies that all arrived around that time, and it was termed the *late heavy bombardment*. Subsequent theorists, though, had difficulty understanding why such a pulse of impacts should have occurred at this relatively late date in Earth's evolution, when the bulk of Earth was known to have formed by 4.4 b.y. ago, or earlier. So, the revisionists suggested instead that the impact flux declined continuously throughout the entire period between 4.5 and 3.8 b.y. ago.

Within the last 4 years, however, a new model of solar system formation has provided support for the original "pulse" theory of the late heavy bombardment. The model is sometimes termed the *Nice model* because several of the coauthors work in laboratories situated near the city of Nice, in southern France. (The name of the city is pronounced "neese," not "nice.") The Nice model provides a possible explanation for why a pulse of bombardment might have occurred at about 3.9 b.y. ago. (See the Box "A Closer Look: The Nice Model of Solar System Formation.") If this model is correct, then the heavy bombardment may have occurred essentially all at once, rather than spread out over hundreds of millions of years. And this, in turn, might have led to a very different evolutionary path for the early atmosphere and for life itself. We should bear this in mind as we discuss the early steps in biological evolution in the remaining parts of this chapter.

Composition of the Early Atmosphere

What would have been the composition and surface pressure of the atmosphere during the earliest few hundred million years of Earth's history? No one knows for sure, but we can make some educated guesses. Free oxygen, O_2, which makes up about 21% of today's atmosphere, should have been virtually nonexistent, because life—and therefore photosynthesis, the source of free oxygen—had probably not yet arisen. Nitrogen, N_2, does not participate very actively in geochemical cycles; hence, most of it should have been in the atmosphere, as it is today, at about 78% of the total. The present partial pressure of N_2 is about 0.8 bar. Nitrogen would have formed from nitrogen-rich organic compounds and ammonia ice (NH_3) in incoming planetesimals. The shock of their impact on Earth's surface should have converted much of this nitrogen to N_2.

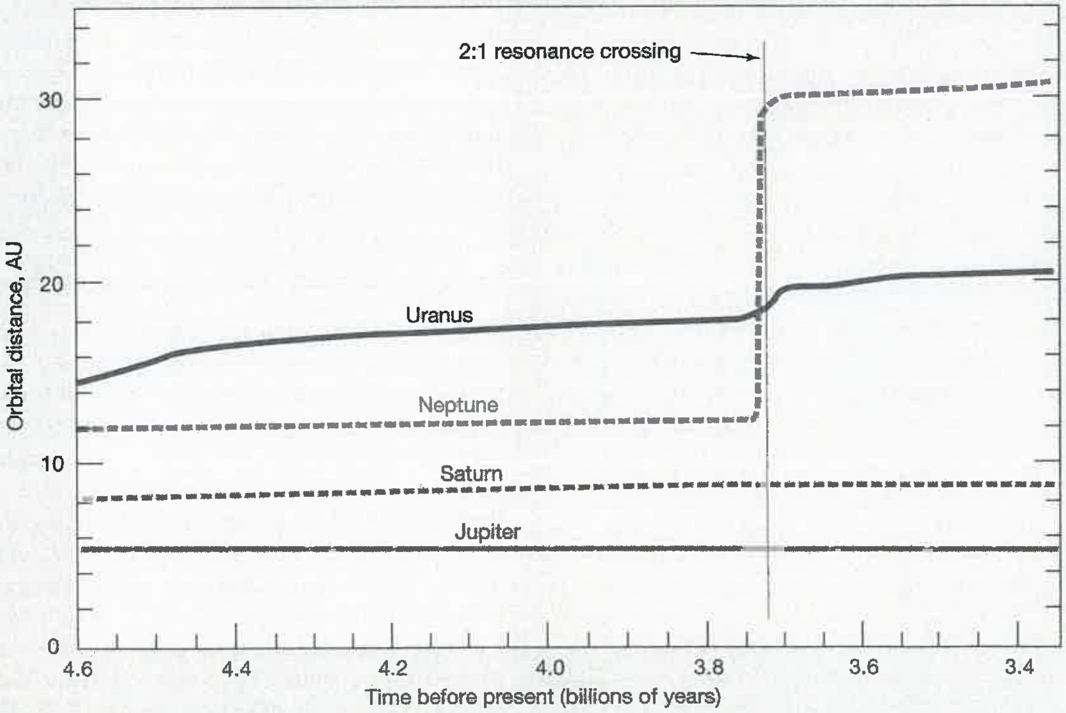
Estimating the CO_2 concentration of the primitive atmosphere is much more difficult. On one hand, we know that Earth's total inventory of carbon is huge—the equivalent of 60–80 bars if it were all oxidized to CO_2. As

A CLOSER LOOK

The Nice Model of Solar System Formation

The authors of the Nice ("neese") model used a sophisticated computer code to simulate the latter stages of planetary accretion. They started their simulation with a more-or-less evenly distributed swarm of Moon-sized planetesimals, and then calculated their mutual gravitational interactions and collisions as they grew into planets. The four giant planets— Jupiter, Saturn, Uranus, and Neptune— were assumed to be fully formed at the beginning of the simulation; however, they were placed at locations that were different from where they are located today. (See Box Figure 10-3.) In the model, Jupiter was assumed to have started slightly farther away from the Sun than it is now, and Saturn started slightly closer in. Uranus and Neptune were assumed to have formed just beyond Saturn's orbit, with Neptune being closer to the Sun than Uranus (the opposite of the situation today). All of these assumptions are plausible, although they are by no means a unique starting point for generating the present solar system.

Once the simulation was started, the giant planets started to move, or *migrate*, from their initial orbital locations. Based on observations of Jupiter-mass planets orbiting close-in around other nearby stars (see Chapter 19), we now know that planets are able to move around during the early stages of planetary system formation. They do so by interacting gravitationally with the remaining dust and gas in the disk and with smaller planetesimals that have not yet been accreted into large planets. In the Nice model simulation, Jupiter migrated inward while Saturn migrated outward. At some time around 3.8 b.y. ago, Saturn's orbital period became exactly twice that of Jupiter. (It is just slightly greater than that now: 29.7 years versus 11.9 years for Jupiter.) The resulting *resonance* between the two planets changed the shapes of both planets' orbits, and this in turn affected the orbits of the two less-massive giant planets, Uranus and Neptune. (We will talk more about shapes of planetary orbits in Chapter 14 when we discuss the astronomical theory of Earth's Ice Ages.) Both of these planets were pushed farther away from the Sun, and Neptune moved from inside Uranus's orbit to beyond it. Although this complicated scenario may sound somewhat ad hoc, it is consistent with what we have learned about giant planet migration by studying planets around other stars. The net result of the simulation was that Uranus and Neptune were suddenly thrown into the outer solar system, which at this time was still filled with icy planetesimals that had not yet had sufficient time to accrete into larger bodies. Most of these planetesimals were subsequently scattered out of their original orbits, with some of them passing through the inner solar system, and a few of these impacting the Moon and the



BOX FIGURE 10-3 Evolution of giant planet orbital distances in the Nice model. The horizontal scale shows time in billions of years before present. The vertical scale shows orbital distance in AU (1 AU = 1 astronomical unit = mean Earth–Sun distance). The vertical line shows the time at which Saturn's orbital period becomes exactly twice that of Jupiter (*Source:* Adapted from K. Tsiganis et al., Nature, v. 435, p. 459, 2005.)

terrestrial planets. If this scenario, or something akin to it, is correct, then the original interpretation of the Moon rocks as representing a pulse of bombardment may well have been correct.

The Nice model is complicated, but it may be testable at some time in the relatively near future. NASA has plans to send astronauts back to the Moon within the next 15 years. With a larger collection of Moon rocks from a wider variety of locations, it should be possible to definitively answer the question of whether the heavy bombardment was continuous, or whether it was a relatively sudden, catastrophic event. And this, in turn, will help us better understand the earliest part of Earth's history and the very early evolution of life.

discussed in Chapter 8, most of this carbon is presently stored on the continents in the form of carbonate rocks such as limestone and dolomite. It was originally delivered to Earth as organic carbon in incoming asteroids and comets. Following the previous discussion, much of this carbon would have been immediately released into the atmosphere by the process of impact degassing. The chemical form of the carbon is difficult to calculate: some models predict that it would have been released as CO (carbon monoxide), while other models suggest that it would have been released as a mixture of CH_4 and CO_2. In either case, most of the carbon would have ended up as CO_2 because it would have been oxidized by photochemical reactions involving water vapor. (See the Box "A Closer Look: Oxidation of the Atmosphere by Escape of Hydrogen.")

Exactly how much CO_2 would have been present in the atmosphere during this earliest period of Earth history is difficult to determine. Almost no rocks have been preserved from this time interval, and those that do exist tell us little or nothing about how much CO_2 was present. Hence, we are forced to rely on theoretical models to try to estimate the CO_2 partial pressure at that time. Unfortunately, different theoreticians get different answers depending on what they think was most important.

If, for example, the continents were originally much smaller, as some geologists believe, the process of silicate weathering on land may have been much slower than today. Because silicate weathering is the long-term loss process for CO_2 (Chapter 8), this would have tended to make the atmospheric CO_2 level higher. Some geologists have predicted that Earth could have had a 10-bar CO_2 atmosphere for the first several hundred million years of its history, until the continents began to grow. In that case, the surface temperature could have been quite hot (80–90°C), in spite of the 30% decreased luminosity of the young Sun.

On the other hand, other geologists point out that CO_2 should have reacted rapidly with the fresh seafloor and with the finely powdered **ejecta** produced by impacts. In that case, atmospheric CO_2 levels could have been quite low, and early Earth would have been very cold. We shall return to the question of the temperature of early Earth in Chapter 12. For now, though, we simply acknowledge that we do not know whether the atmosphere was thick or thin during the earliest stages of Earth's history, and we are equally uncertain whether the climate was warm or cold. This might not matter much, either, except that life may have originated during this era, and some theories of life's origin depend strongly on the ambient temperature. We'll consider how that might have happened in the next section.

THE ORIGIN OF LIFE

The question of how life on Earth originated has been a topic for both religious and scientific speculation. Nearly all religions have their own creation "myths." While many of these stories have considerable moral and intellectual value, most are directly contradicted by the geologic record on Earth and by the sheer immensity of geologic time. For example, a literal reading of the Bible implies that God created Earth and all forms of life over a space of 7 days only a few thousand years ago. We saw earlier in this chapter that radiometric dating places the age of Earth at over 4.5 billion years. Unless the laws governing radioactive decay change with time themselves, an unlikely possibility, the biblical creation story cannot be true in a literal sense. A Creator or Supreme Being could indeed have played a role in the creation of both the universe and life, but if so, both events must have happened a very long time ago.

The modern scientific theory of life's origin was first formulated in the 1920s by Russian scientist Alexander Oparin and independently by British scientist J. B. S. Haldane. The *Oparin–Haldane hypothesis,* as it came to be called, postulated that life arose from chemical reactions that were initiated in a strongly reduced early atmosphere and came to completion in the early oceans. Recall that reduced carbon is carbon that is bonded to other carbon atoms or to hydrogen. A **strongly reduced atmosphere** is one that is rich in hydrogen-containing gases, such as methane (CH_4) and ammonia (NH_3). Oparin and Haldane proposed that energy sources such as sunlight and lightning caused these gases to react with each other to form organic compounds in a process termed **chemical evolution**. Ultimately, and in a manner that admittedly is still not understood today, these organic compounds assumed the characteristics of living systems. (See the Box "A Closer Look: What Does It Mean to Be Alive?")

The Miller–Urey Experiment

The Oparin–Haldane theory of life's origin received a gigantic boost from a series of laboratory experiments performed in 1953 by a graduate student at the University of

A CLOSER LOOK

Oxidation of the Atmosphere by Escape of Hydrogen

The compounds that formed Earth's primitive atmosphere were initially highly reduced. Recall from Chapter 8 that reduced carbon is carbon that is bonded to other carbon atoms, hydrogen, or nitrogen. Most of the carbon in meteorites is in the form of reduced or organic carbon, and this was presumably true of the planetesimals from which Earth formed as well. When these planetesimals impacted the young planet, much of the carbon would have been released as the reduced gases CO and CH_4. It would not have remained in those forms very long, however. In the absence of oxygen and ozone, ultraviolet radiation from the Sun would have **photolyzed** (split apart) water molecules, creating hydrogen atoms (H) and **hydroxyl radicals** (OH):

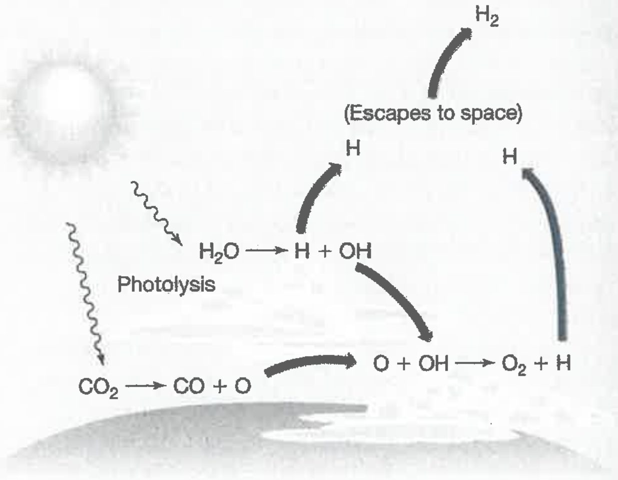
$$H_2O + \text{UV photon} \rightarrow H + OH.$$

(A *radical* is a molecule that is highly reactive because it has an unpaired electron in its outer shell.) OH radicals play an important role in today's atmosphere, where they are responsible for oxidizing various gases, including CH_4 and CO. In the case of CO, the reaction is

$$CO + OH \rightarrow CO_2 + H.$$

For CH_4, the reaction sequence is more complicated but the result is the same: the carbon ultimately ends up as CO_2.

What makes these reactions important is the fact that they are essentially irreversible. The hydrogen atoms that are produced are light enough to escape from Earth's atmosphere. As this happens, both CO and CH_4 are converted irreversibly to CO_2. Hence, Earth's atmosphere tends to become more oxidized with time, simply because hydrogen is always being lost to space. Note, however, that this process does *not* produce free oxygen, O_2. A very small amount of O_2 can be produced by other reactions, as described later in the chapter, but almost all of the O_2 in our present atmosphere was produced by photosynthesis.



BOX FIGURE 10-4 Diagram illustrating escape of hydrogen to space and resultant oxidation of the early atmosphere.

Chicago, Stanley Miller, working under the guidance of famous geochemist Harold Urey. Miller and Urey filled flasks with mixtures of gases that were considered at that time to be representative of Earth's primitive atmosphere. (These gases had just recently been discovered in Jupiter's atmosphere. Because Jupiter does not lose hydrogen, its atmosphere was considered by Urey to be "unevolved." Urey reasoned, not quite correctly, that Earth's atmosphere would have been similar in composition before hydrogen had had time to escape.) The flasks contained methane and ammonia, along with water vapor and molecular hydrogen. The researchers then sparked the flasks with powerful electric discharges, simulating lightning in the prebiotic atmosphere.

After several minutes of electrification, the walls of the flasks became coated with a sticky, brownish material. When analyzed, this material was found to contain an assortment of organic compounds, including amino acids. **Amino acids** are compounds—containing an amino group (NH_2) and a carboxyl group (COOH)—that are important building blocks for proteins (see the Box "A Closer Look: The Compounds of Life"). **Proteins**, composed of one or more chains of amino acids, are key molecules in organisms. Proteins may be *enzymes* (guiding chemical reactions), structural components, *hormones* (maintaining constant body conditions), or transport molecules.

The Miller–Urey experiment, as it is now called, made headlines around the world. It was indeed a revelation

A CLOSER LOOK

Prebiotic O_2 Concentrations

How much O_2 would have been present in the atmosphere prior to the origin of life? We already know that most of Earth's O_2 was produced by photosynthesis. This, of course, is a biological process. We would like to know the prebiotic atmospheric O_2 level for two reasons: (1) free O_2 would have poisoned the chemical reactions leading to the origin of life, as discussed in the text; and (2) if prebiotic O_2 levels were low on Earth, then the presence of O_2 in another planet's atmosphere may be a useful indicator that life is present. As we will see in Chapter 19, scientists hope to eventually look for the presence of O_2 in the atmospheres of planets around other stars to determine whether such planets might be inhabited.

How could O_2 have been produced in the absence of photosynthesis? Probably the most important mechanism for producing O_2 abiotically is the following. First, water vapor is photolyzed by a UV photon, producing atomic hydrogen (H) and a hydroxyl radical (OH):

$$H_2O + \text{UV photon} \rightarrow H + OH.$$

Then, another UV photon splits a CO_2 molecule, producing carbon monoxide (CO) and atomic oxygen (O):

$$CO_2 + \text{UV photon} \rightarrow CO + O.$$

The OH and O radicals then combine to form O_2:

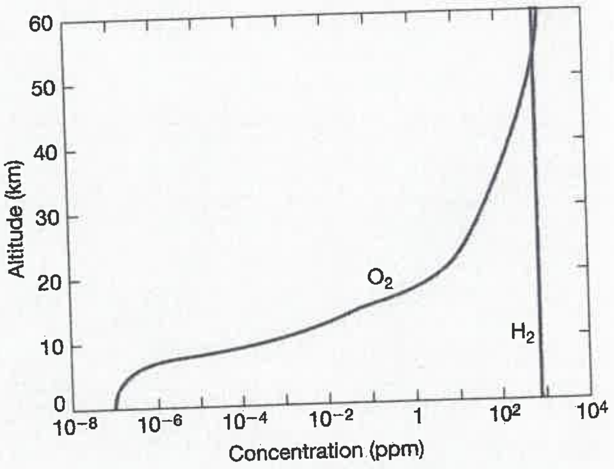
$$O + OH \rightarrow O_2 + H.$$

If the hydrogen atoms produced in these reactions escape to space, which they can do because they are light, then a net production of O_2 has occurred.

This does *not* necessarily imply that O_2 will build up in the atmosphere of an abiotic planet, however, because there are also loss processes for O_2 that tend to remove oxygen as fast as it is produced. The most important of these is oxidation of reduced volcanic gases, such as H_2 and CO. These gases do not react directly with O_2 at room temperature (unless one provides a flame to get them started!). However, they can react with oxygen indirectly by way of reactions that involve the by-products of water vapor photolysis. The net result is

$$2\,H_2 + O_2 \rightarrow 2H_2O$$
$$2CO + O_2 \rightarrow 2CO_2$$

Thus, the oxygen reacts with these reduced gases to form H_2O and CO_2. When one studies these processes with detailed models, one finds that such reactions will quickly use up almost all of the O_2 produced by the photolysis of H_2O and CO_2, followed by the escape of hydrogen to space. The net result is a **weakly reduced atmosphere** with a composition similar to that shown in Box Figure 10-5. (Evidently, the amount of free O_2 generated by photochemical reactions in an early Earth-type atmosphere is extremely low. Hence, the presence of O_2 in a planet's atmosphere is a strong indication of the presence of life.)



BOX FIGURE 10-5 Vertical profiles of H_2 and O_2 in a weakly reduced primitive atmosphere.

to discover that many of the basic compounds on which life depends can be synthesized by a straightforward process that could have occurred in nature. Many scientists working in this field thought that we might be close to understanding how life itself began.

Today, the Miller–Urey experiment is still held in high regard scientifically, but researchers are less certain that it represents a critical step in the origin of life. One reason is that just mentioned: Current theories of the early atmosphere suggest that it was not as strongly reducing as the gas mixtures in Stanley Miller's flasks. Methane and ammonia, if they were present at all, would probably have been held to relatively low concentrations because they are photolyzed by solar UV radiation. The hydrogen then escapes to space, and the carbon and nitrogen atoms left behind are converted into CO_2 and N_2. Furthermore, modern volcanos do not emit much methane or ammonia. Early volcanic gases might have been more highly reducing; however, even this was probably not enough to produce a Miller–Urey-type atmosphere.

The RNA World

A second way in which our ideas about the origin of life have changed is that most biologists now believe that proteins were not among the earliest structural elements of life. Rather, life might have relied exclusively on RNA or some simpler variant of RNA. (See Box "A Closer

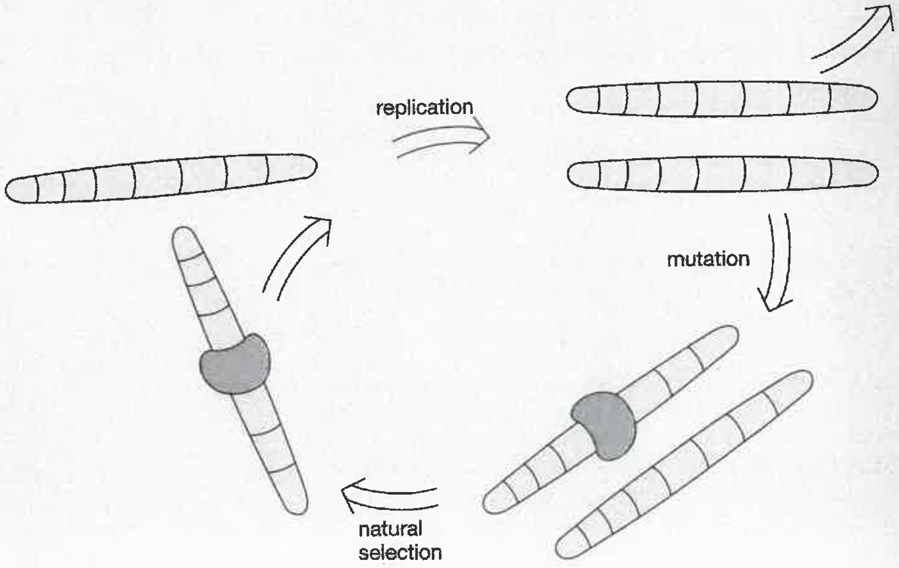
A CLOSER LOOK

What Does It Mean to Be Alive?

Almost anywhere we go on Earth today, we can see things that we know are alive: plants, animals, insects, people, and other **organisms**. How do we know that these various, extremely different things are alive?

It is surprisingly difficult to come up with a good definition of life. The ability to move, for example, is not an identifying characteristic of life because while animals move, plants do not. Also, many inanimate objects, cars for example, move under their own power. At a chemical level, all organisms that we know of consist of organic (carbon-based) compounds and are reliant on the presence of liquid water during at least part of their life cycles. However, we cannot be certain that this is true of life in general. Carbon is particularly well suited for making long chains and big, complex molecules, so it may well be that all life is carbon based. However, biologists still seek some more general definition.

The definition of life that is generally quoted by biologists is based on Charles Darwin's theory of evolution. According to this theory, organisms evolve by way of the combined processes of **replication**, **mutation**, and **natural selection** (Box Figure 10-6). As the name suggests, *replication* is the process by which an organism reproduces itself. Given that all organisms have a finite (and relatively short) life span, life obviously could not exist for very long if organisms were unable to replicate. *Mutation* simply means that the replication process is not exact, that is, the organisms that are produced can in some instances be different from the original organisms. If not for mutation, organisms could not evolve into different and more complex forms. *Natural selection* refers to the process by which certain, better-adapted organisms survive in greater numbers than do others. Thus, a favorable mutation can lead to a new type of organism that may gradually replace the old organism or, alternatively, to an organism that is capable of living in some different environment. Through this combined process of replication, mutation, and natural selection, life has evolved into a myriad of different forms that have successfully colonized nearly all parts of Earth's surface.



BOX FIGURE 10-6 Cartoon illustrating the processes of replication, mutation, and natural selection, by which life is defined.

Look: The Compounds of Life" for a description of what RNA, DNA, and proteins consist of chemically.)

The evidence that RNA preceded proteins was discovered in the mid-1980s by Thomas Cech of the University of Colorado and Sydney Altman of Yale University, and it earned them the 1989 Nobel Prize in chemistry. Cech and Altman discovered that one particular type of RNA molecule was capable of cleaving (cutting) itself into smaller pieces. This capability meant that it was theoretically possible for an RNA molecule to replicate (duplicate) itself without help from any other molecule. DNA-based organisms cannot do this. The DNA molecule can replicate only with the aid of complex enzymes made of proteins. An **enzyme** is a biological molecule that speeds up, or *catalyzes*, a particular biochemical process.

Life depends on a complex interaction among DNA, RNA, and proteins. The DNA carries the basic genetic information (the blueprint for the organism); the RNA is used to transfer this information to other parts of the cell, where proteins are made; and the proteins perform many different cell functions, including the replication of DNA and RNA.

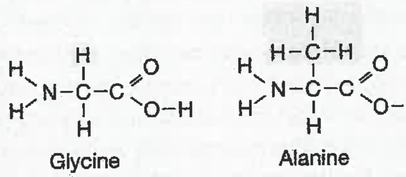
A primitive, RNA-based organism could have been much simpler than today's organisms. RNA itself could have been the molecule in which the genetic information was stored. RNA is less stable than DNA, but it carries

A CLOSER LOOK

The Compounds of Life

Life depends on a complex array of organic (carbon-containing) compounds that organisms use to perform different tasks. Perhaps the most fundamental of these compounds are amino acids and nucleic acids. Amino acids are the building blocks of proteins, which are essential to many different cell functions. Nucleic acids, which include both ribonucleic acid (RNA) and deoxyribonucleic acid (DNA), are the carriers of genetic information. DNA stores this information, and RNA transfers the information to different parts of the cell and makes proteins and other compounds.

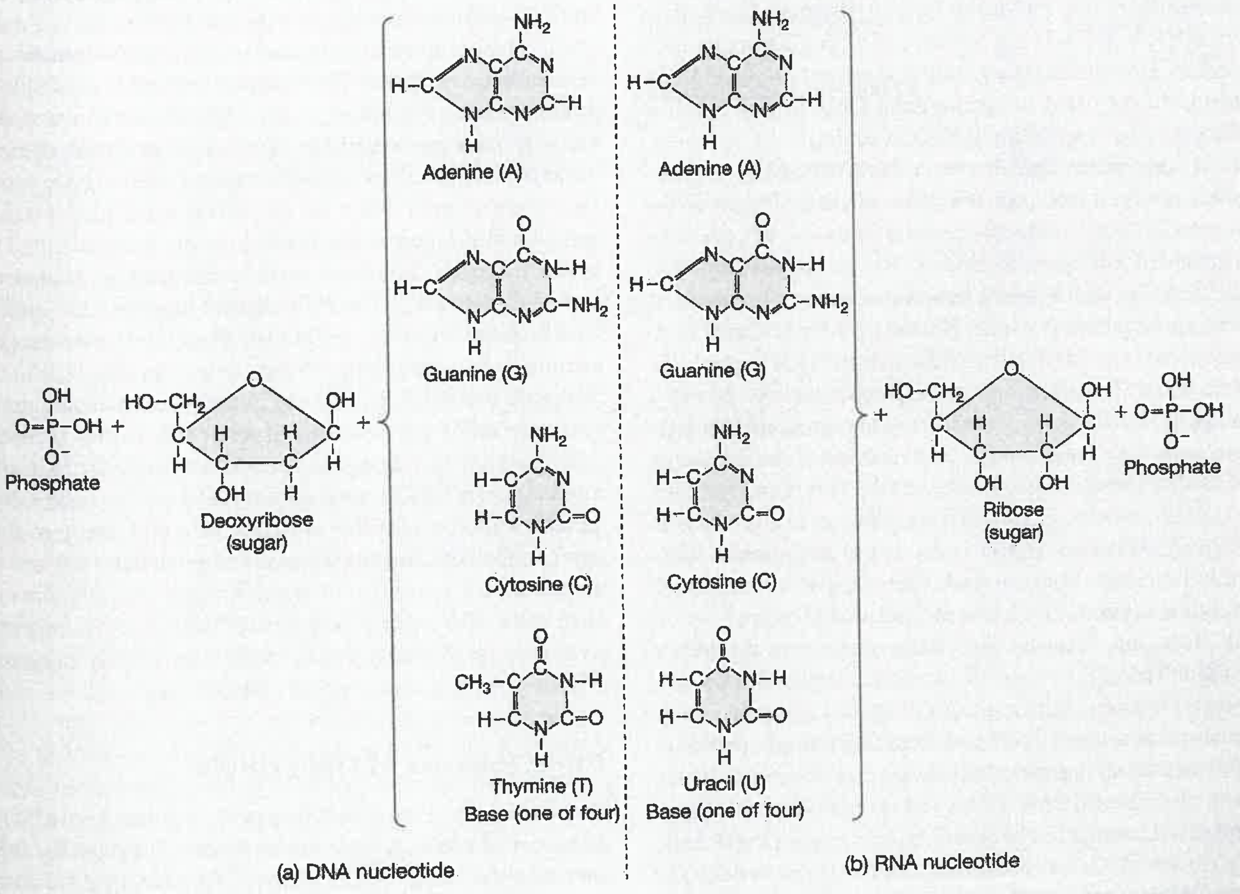
Chemically, an amino acid is an organic compound that contains an amino group (NH_2) and a carboxyl group (COOH). The two simplest ones are glycine and alanine (Box Figure 10-7). These compounds are similar except for the side chain: The hydrogen atom, H, in glycine is replaced by a methyl group, CH_3, in alanine. Other amino acids have more complicated side chains containing oxygen, nitrogen, or sulfur. Twenty different amino acids are found in naturally occurring proteins, but many other amino acids are chemically possible.



BOX FIGURE 10-7 Two of the simpler amino acids found in proteins.

RNA and DNA are more complicated compounds that consist of chains of molecules called **nucleotides**. Each nucleotide consists of three parts. In RNA, these include a phosphate molecule, a ribose (sugar) molecule, and a nitrogen-containing base. The base can be any of four molecules: adenine (A), guanine (G), cytosine (C), or uracil (U) (Box Figure 10-8). The nucleotides in RNA are linked together in a long, single strand.

A DNA nucleotide is similar to an RNA nucleotide except that the sugar molecule is deoxyribose instead of ribose and that one of the four bases, uracil, is replaced by thymine (T). The DNA nucleotides are strung together in two chains that form a double helix. This double-stranded, twisting structure was discovered in 1953 by James Watson and Francis Crick. The sequence of bases in DNA carries information in the form of the genetic code. Groups of three individual nucleotides code for specific amino acids. For example, the sequence CCA codes for glycine and CGA codes for alanine.



BOX FIGURE 10-8 Structural diagrams of the components of (a) DNA and (b) RNA. (*Source:* G. S. Kutter, *The Universe and Life*, Boston: Jones and Bartlett, 1987.)

essentially the same information. And because it can cleave itself, RNA could have reproduced without the aid of enzymes. The elegance and simplicity of this idea has led biologists to suggest that DNA-based life was preceded by an **RNA World**, in which only RNA-based organisms were present.

Even if this idea is correct, it does not solve the problem of life's origin. We still need to make the basic compounds of which RNA is composed and then assemble them into a self-replicating molecule. The required phosphate molecules were probably present in the primitive ocean as a result of weathering of rocks, but ribose and the four nitrogen-containing bases have more complicated structures that may or may not have been easy to form.

Prebiotic Synthesis of Organic Compounds

In the Miller–Urey experiment, the investigators found that they could synthesize amino acids by starting from gaseous mixtures that contain methane and ammonia. If RNA-based organisms came first, the first requirement for originating life would have been to synthesize ribose and the four bases adenine, guanine, cytosine, and uracil. Alternatively, the earliest organisms could have used simpler compounds that later evolved into RNA, but this scenario presents the difficult problem of how life could have switched from one molecular basis to another. (Switching from RNA to DNA is not considered difficult from an evolutionary standpoint because the molecules are so similar. Indeed, the first step in synthesizing DNA within a cell is to form the corresponding RNA molecule.)

Could ribose and the bases have formed from compounds present in the primitive atmosphere and oceans? We can get a clue by looking at chemical formulas. The molecular formula for ribose is $C_5H_{10}O_5$. (The corresponding structural formula, which shows how the atoms are arranged, is shown in Box Figure 10-8b.) Simple division shows that ribose can be formed from five molecules of H_2CO—the compound *formaldehyde,* which is commonly used to preserve dead animals. (If you dissected a frog in high school biology class, you may recall its distinctive smell.) The molecule H_2CO should not be confused with the shorthand notation for organic carbon, CH_2O, that we have used elsewhere in this book. Whereas H_2CO is an actual molecule, CH_2O merely represents complex hydrocarbons that have approximately the same relative ratios of C, H, and O atoms.

Thus, the first step in forming ribose is to synthesize formaldehyde. This step, it turns out, is easily accomplished. Photochemical reactions in weakly reducing, CO_2-rich atmospheres are predicted to produce large quantities of formaldehyde. Because formaldehyde is soluble in water, much of it should have dissolved in rainwater and been transported into the early ocean. Converting formaldehyde into ribose is also not difficult, because formaldehyde spontaneously reacts to form sugars in water solution. The problem for life's origin, which we will not discuss here, is that lots of other sugars form in addition to ribose and that these molecules might have interfered with the synthesis of RNA. What we can say is that the necessary starting material for forming ribose should have been available.

What about the four bases—could they have been formed on the prebiotic Earth? Let us take the same approach and begin with chemical formulas. For simplicity, we consider only the simplest base, adenine. Its molecular formula is $C_5H_5N_5$. Evidently, adenine can be formed from five molecules of HCN, *hydrogen cyanide.* Hydrogen cynanide is an extremely deadly poison to most higher organisms. To prebiotic chemists, however, it is considered an essential building block for life.

Forming hydrogen cyanide in the prebiotic atmosphere is more difficult than forming formaldehyde. In a Miller–Urey-type atmosphere containing methane and ammonia, HCN would have been generated by lightning. In a weakly reduced, CO_2–N_2 atmosphere, lightning would not have sufficed because the carbon and nitrogen atoms produced by the lightning would have combined with oxygen atoms from the CO_2. However, the primitive atmosphere might have contained a few tens of parts per million of methane, CH_4. Methane photolysis in the stratosphere produces molecular fragments that can combine with N atoms that flow down from the ionosphere, forming HCN. The N atoms are produced from the breaking apart of the ion N_2^+ when it recombines with an electron.

The key to this mechanism is to identify a source for atmospheric methane. The methane in today's atmosphere is almost entirely of biological origin. However, some abiotically generated methane is released in fluids coming from hydrothermal vents at mid-ocean ridges. These vents, which are described in more detail below, are places where hot, mineral-laden water flows into the deep ocean. The water contains dissolved carbon compounds, including both CO_2 and CH_4. The fluids emanating from the hottest vents contain mostly CO_2, but the cooler, off-axis vents on certain, slow-spreading ridges (e.g., the Mid-Atlantic Ridge) are rich in CH_4 and H_2. These gases are thought to be produced by a process called **serpentinization**, a chemical reaction in which seawater reacts with **ultramafic rocks** (rocks rich in magnesium and iron) to form compounds called *serpentine minerals.* We will return to this topic in the next chapter because it may bear on the rise of atmospheric oxygen. For now, though, we simply point out that some abiotically produced methane should have been available on the early Earth even if the highly reduced, Miller–Urey-type atmosphere never existed.

Other Theories of Life's Origin

Some researchers remain skeptical that life could have formed on Earth's surface or in its oceans. Although the fundamental building blocks of life, H_2CO and HCN, were probably available, the chance that they would have been concentrated sufficiently to allow further reactions to occur might have been small. And the more complex organic compounds that might have formed in this way would not have lasted long in the surface-ocean environment, because they would have been destroyed by photochemical and thermal (heat-driven) reactions. Therefore, researchers have sought alternative ways of forming complex organic compounds.

One possibility is that the relevant organic compounds were formed in space and brought to Earth by asteroids or comets or as tiny dust particles. **Interplanetary dust particles (IDPs)** are small particles recovered from the stratosphere that are known to be of extraterrestrial origin. We know that organic compounds, including amino acids, exist in IDPs as well as in some meteorites. Indeed, amino acids and many other complex organic compounds have now been identified in interstellar dust clouds (Figure 10-2). They are believed to form from reactions between ions and neutral molecules that occur at very low temperatures. Typical temperatures in interstellar dust clouds are on the order of 10 K, not much above absolute zero. It may seem surprising that organic chemistry could occur in this environment, but it is precisely the extremely low temperatures involved that allow complex organic molecules to exist. The organic molecules form from reactions between other molecules and ions (charged particles), and then they live for long times because temperatures are too cold to allow them to decompose.

Some of the molecules formed in the interstellar environment are thought to have survived the collapse of the cloud that formed our own Sun and solar nebula. They would have been incorporated into solid materials that condensed out of the nebula and accreted to form asteroids and comets. Such materials might have been delivered to Earth in great quantities during the heavy bombardment period of solar system history, between 4.5 and 3.8 b.y. ago.

A third theory of life's origin is that it took place in or around **hydrothermal vents** in the mid-ocean spreading ridges. Recall from Chapter 7 that mid-ocean ridges are places where new seafloor is being created. The ridges are cooled by seawater that flows a kilometer or more down through cracks in the rock, is heated, and then rises rapidly back to the surface. In the process, the water picks up reduced substances such as hydrogen (H_2), hydrogen sulfide (H_2S), and dissolved ferrous iron (Fe^{2+}). *Ferrous iron* is a reduced form of iron that is soluble in seawater. When it hits the cold water, the hot (350°C) vent water produces a dark plume of precipitating material called a **black smoker** (Figure 10-6). The majority of the dark material is iron sulfide, FeS, produced by the reaction between ferrous iron and hydrogen sulfide.

Are submarine hydrothermal vents a likely place for life to have originated? The vent systems are rich in the types of reduced materials from which organic molecules can be synthesized. They contain liquid–solid interfaces that some researchers think are needed to organize organic molecules into specific patterns. One model suggests that life originated on the surface of *pyrite* (FeS_2) mineral grains, which are abundant in hydrothermal vent systems.

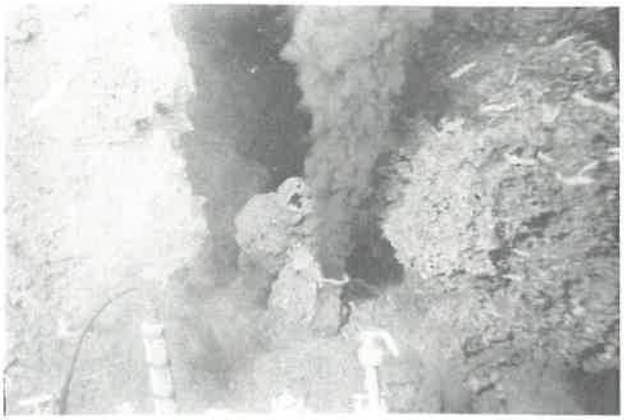


FIGURE 10-6 [See color section] Picture of a black smoker. (*Source:* Ken MacDonald/SP/Photo Researchers.)

However, complex organic molecules are not stable at the high (350°C) temperatures observed in vents located directly on the ridge axes. If life did originate at the mid-ocean ridges, it probably did so in cooler, off-axis vents. Some researchers argue that even the off-axis vents are too warm and that the best place for life to have originated would be in some near-freezing surface environment. The debate as to whether life originated in a hot or cold environment is likely to continue until we have a better idea of how the process actually occurred.

When Did Life Arise?

Thus far, we have discussed how life may have arisen but we have not talked about when this event occurred. The question of when life originated is currently the topic of much debate. Until about the middle of the last century, **paleontologists** (geologists who study fossils) believed that life originated only about 540 m.y. ago at the dawn of the Cambrian period. Fossils of this age or of more recent time periods are easy to find because the organisms that formed them were large enough to see with the naked eye and because many of them formed shells of silica or calcium carbonate that became preserved within sedimentary rocks. In the 1940s, though, paleontologists such as Elso Barghoorn at Harvard University began to discover **microfossils**. As their name implies, microfossils are the fossilized remains of tiny, single-celled organisms (or, in some cases organisms formed of chains of individual cells). Unlike **macrofossils** (the remains of multicellular organisms), microfossils are difficult to find and even more difficult to classify. And it is easy to be confused between bonafide microfossils and structures that look like microfossils but are formed abiotically. During the early 2000s, a vigorous debate occurred over what had been thought to be the world's oldest microfossils (see Figure 10-7). These specimens were collected from the Apex Chert, which is part of the 3.5 b.y.-old Warrawoona Formation in Australia, by paleontologist J. William Schopf from the University

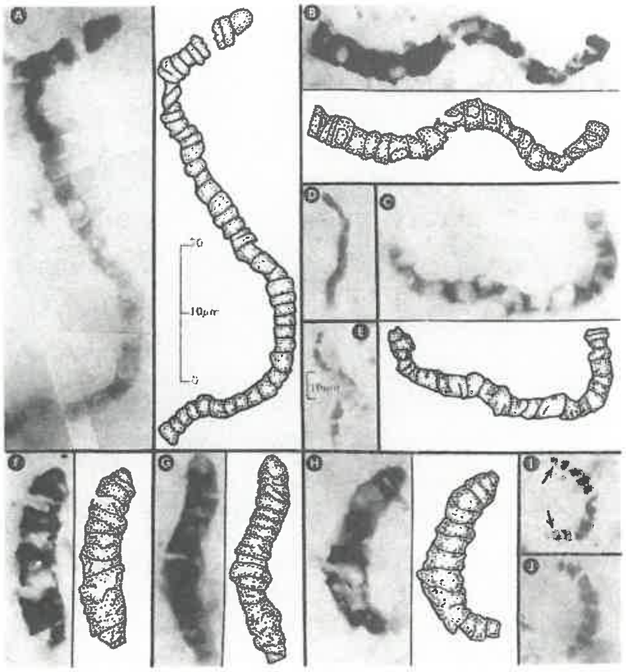


FIGURE 10-7 Apex Chert "microfossils." These structures are from the 3.5 b.y.-old Warrawoona Formation in Australia. A debate is currently raging as to whether they are biogenic or not. (*Source:* J. William Schopf.)

of California, Los Angeles, and they do indeed look remarkably like some modern bacteria. (See further discussion in Chapter 12.) But British paleontologist Martin Brasier and his colleagues argued that these structures are not biological at all. Rather, they think that these are bits or chains of organic carbon that formed abiotically within fluids emanating from a hydrothermal vent. The jury is still out as to whether the organic carbon is or is not biological in origin. However, most researchers would probably agree that these microfossils are not what they were originally interpreted to be.

Regardless of who turns out to be right about the Apex Chert microfossils, it does appear that life had originated by 3.5 b.y. ago or slightly thereafter. Many more structures that are plausible microfossils have been found in slightly younger rocks, along with macroscopic structures called *stromatolites,* which we will discuss in Chapter 12. More interesting is the question of whether life had originated even earlier. *Isotopically light* organic carbon has been found in 3.85 b.y.-old rocks from Isua, West Greenland, and from nearby Akilia Island. By "isotopically light," we mean that the organic carbon is depleted in the heavier ^{13}C isotope compared to the normal ^{12}C isotope. As we will discuss in more detail in the next chapter, metabolic processes such as photosynthesis tend to discriminate against the heavier carbon isotope, so "light" organic carbon is usually considered to be evidence for biological activity. However, some abiotic processes can also favor one isotope over another. Furthermore, some (but not all) of the rocks in which this organic carbon has been found have recently been reclassified as being of igneous, rather than sedimentary, origin. It is difficult to imagine how biologically generated carbon could end up trapped within a rock that formed from a molten magma. So, the jury is still out on this question as well. But it is certainly possible, even likely, that life was already around by 3.8–3.9 b.y. ago.

The Universal Tree of Life

Some of the most useful information concerning the origin of life comes from studying modern organisms. Over the past two decades, molecular biologists have learned to sequence both RNA and DNA. Sequencing a molecule of nucleic acid means determining the order of the individual nucleotides. Recall that a nucleotide consists of one of four bases attached to a ribose molecule for RNA, or deoxyribose, for DNA, which in turn is connected to other nucleotides by phosphate linkages. (See the Box, "A Closer Look: The Compounds of Life.") By using powerful new techniques such as **polymerase chain reaction (PCR)**, biologists have been able to unravel the genetic code of all sorts of different organisms, including humans. Both DNA and RNA are extremely large and complicated molecules that contain information about every facet of an organism. Particular parts of these molecules can be used to look way back into early evolutionary history. The particular molecule that has been found to be most useful is the RNA found within **ribosomes.** The ribosome is a part of the cell in which proteins are manufactured. All organisms have ribosomes and ribosomal RNA, which makes this molecule useful for making comparisons. Protein manufacture is also an extremely ancient and slowly evolving metabolic capability, so sequencing ribosomal RNA provides a way of looking deeply into evolutionary history. Because PCR acts on DNA, not RNA, this is actually done in practice by sequencing the part of the DNA molecule that codes for ribosomal RNA, but it is essentially the RNA sequences that are being compared.

The results of comparing sequences of ribosomal RNA from various organisms can be used to draw an evolutionary "tree" (Figure 10-8). This tree was first constructed by Carl Woese at the University of Illinois and his graduate student, George Fox. It shows that organisms can be divided into three main categories, or **domains**: **Bacteria**, **Archaea**, and **Eukarya**. The Bacteria and Archaea are both composed entirely of single-celled organisms that we commonly refer to as *bacteria.* The Eukarya contain some single-celled organisms as well, such as the intestinal parasite *Giardia,* but they also include all higher plants and animals, including humans. As Figure 10-8 shows, humans (*Homo*) and corn (*Zea*) are closely related to each other by comparison to the very deep divisions that occur between the three different domains of life.

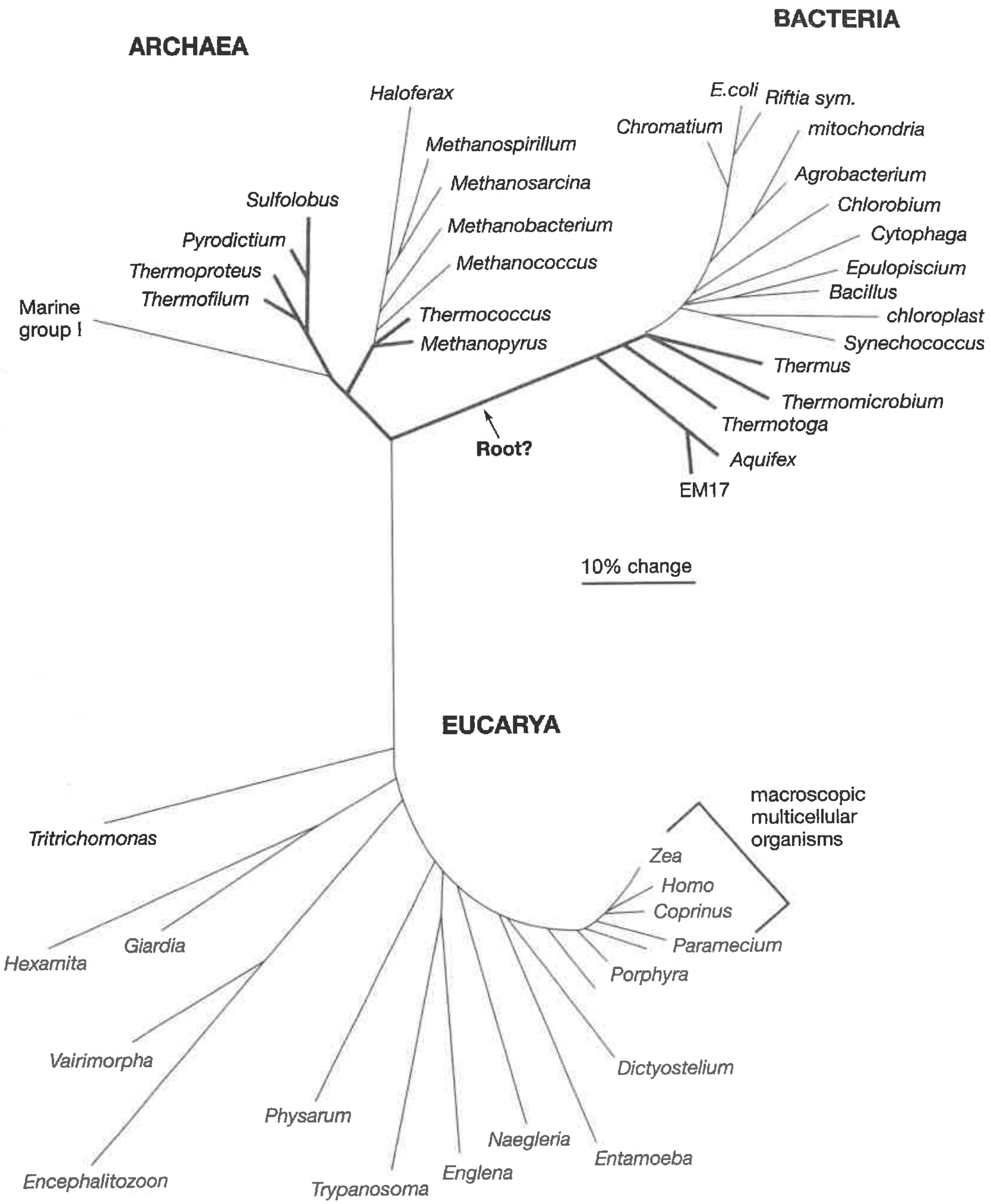


FIGURE 10-8 The Universal Tree of Life derived by sequencing ribosomal RNA. (*Source:* Courtesy Norman Pace, University of Colorado.)

A Hyperthermophilic Last Common Ancestor?

All sorts of interesting information can be derived from this Tree of Life, and we shall take advantage of some of it in the next chapter when we discuss the rise of oxygen. For now, though, let us concentrate on the shaded branches near the point at which the Archaea and Eukarya split from the Bacteria. This point is thought to lie close to the common ancestor of all life.

The shaded branches represent **hyperthermophilic bacteria**—organisms that live at temperatures above 80°C. Surprisingly, nearly all of the organisms near the "root" of the tree are hyperthermophiles. Today, by contrast, hyperthermophiles are restricted to a few unusual environments, such as the mid-ocean ridge vent systems and geothermal hot spots like Yellowstone National Park.

What is the Tree of Life telling us? Does this imply that life originated in a hot environment like the mid-ocean ridge hydrothermal vents? Maybe. But there are other possibilities as well. Some biologists believe that this is merely an artifact of the fact that guanine-cytosine (G-C) bonds in DNA are slightly more stable at high temperatures than are adenine-thymine (A-T) bonds. The DNA of hyperthermophiles has therefore evolved to be rich in G-C bonds, so these organisms all tend to cluster together and to look artificially "ancient." But it might also be telling us something very interesting. Remember, at least some scientists believe that life originated prior to 3.8 b.y. ago. This would have been within the heavy bombardment period discussed earlier in this chapter. Or, alternatively, it would have been prior to the pulse of heavy bombardment at 3.8 Ga predicted by the Nice model. ("Ga" means "gigannum," or billions of years ago.) In either case, Earth was still being pummeled by large comets or asteroids after life had originated. Some of these impacts may have been large enough to vaporize the uppermost layers of the ocean and to completely sterilize the land surface. Suppose that life originated in some cool surface environment and then proceeded to colonize most of Earth's surface, including the mid-ocean ridge vents. Suppose further that, after this had occurred, a giant impactor hit Earth and destroyed all of the surface-dwelling organisms. The mid-ocean ridge dwellers would have been protected from all but the very largest impacts because they were sheltered underneath 2–3 km of ocean. Once the effects of the collision on Earth's surface had died down, roughly 1,000–2,000 years following the impact, organisms from the vent systems could have begun the process of recolonizing. So, it may be that the last common ancestor of all modern organisms was indeed a hyperthermophile, even though the origin of life itself took place in some cooler environment. The information in the Tree of Life does not allow us to distinguish between these two possibilities.

Chapter Summary

1. Earth formed from accretion of solid materials that condensed out of the solar nebula soon after the Sun itself formed.
   a. The age of Earth is identical to that of meteorites, 4.55 b.y., as determined by radiometric age dating.
   b. Earth's core probably formed as Earth itself was forming as a result of heating and stirring by large impacts.
2. The Moon is thought to have formed as a consequence of a glancing impact by a Mars-sized planetesimal and, hence, is something of a cosmic accident.
3. Earth's atmosphere and ocean formed along with the planet from impact degassing of incoming planetesimals and from volcanic outgassing. The resulting atmosphere was probably rich in N_2, and possibly CO_2, but contained little O_2 prior to the origin of life and the evolution of photosynthesis.
4. Life originated on Earth by a process termed *chemical evolution.*
   a. This process may have occurred on Earth's surface using chemicals formed by energetic processes within the atmosphere.
   b. Alternatively, it may have formed from chemicals synthesized in space and imported in interplanetary dust particles or from chemicals synthesized in hydrothermal vents at mid-ocean ridges.
5. Much of what we know about the early evolution of life comes from analyzing ribosomal RNA, or the DNA equivalent thereof.
   a. Strong evidence shows that RNA preceded DNA as an informational molecule.
   b. Weaker evidence indicates that the common ancestor of all extant organisms lived in a hot environment. This could be explained either by a high temperature origin of life or by extinction of non-hyperthermophilic organisms by a giant impact. The latter hypothesis is consistent with life having originated during the heavy bombardment period prior to 3.8 b.y. ago.

Key Terms

accretion
amino acids
Archaea
Bacteria
black smoker
chemical evolution
chondrites
domains
ejecta
enzyme
eon
Eukarya
giant impact hypothesis
heavy bombardment period
Hertzsprung–Russell (H–R) diagram
hydrothermal vents
hydroxyl radicals
hyperthermophilic bacteria
IDPs
impact degassing
interplanetary dust particles (IDPs)
interstellar clouds
isochron diagram
lead–lead dating
macrofossils
magma ocean
main sequence
meteorites
microfossils
migration
mutation
Nice model
natural selection

nucleotides
organisms
paleontologists
photolyzed
planetesimals
polymerase chain reaction (PCR)
proteins
proto-Sun
replication
ribosomes
RNA world
serpentinization
shelly fossils
solar nebula
strongly reduced atmosphere
terrestrial planets
ultramafic rocks
volatile compounds
weakly reduced atmosphere
zircon

Review Questions

1. How old is the solar system, and how is this age determined?
2. How is the age of Earth determined if no rocks older than 4.1 billion years have been preserved?
3. How do Jupiter and the Moon affect the habitability of Earth?
4. How and when did the atmosphere and ocean form? Which gases are thought to have been present in the early atmosphere?
5. In what types of environments might life have originated?
6. Why is RNA thought to have preceded DNA in evolution?
7. How is the Universal Tree of Life constructed?
8. Into what three different domains are modern organisms divided?
9. List two possible reasons why organisms near the base of the Tree of Life are hyperthermophilic.

Critical-Thinking Problems

Write a one- to two-page typewritten essay on the following question:

1. What do you feel is the best theory for how life originated? Do you think that life might exist elsewhere besides Earth?

Further Reading

General

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