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CHAPTER 1
What Is It about Planet Earth?

I'm sitting on the train, as I often do, traveling between Odense and Copenhagen. We've just pulled from the stop at Ringsted. I look out the window. The scene is typical Danish countryside of mixed farmland and forest. I pass cows grazing lazily in the field, and beyond them, a farmer is cutting hay. High above, a hawk searches for mice in the uncut grass. I love this landscape. It reminds me of the Ohio countryside where I grew up. Not spectacular, but somehow comforting and reassuring; an honest landscape not prone to bragging or trickery. I squint, and the landscape merges into a mass of green, the cows become ghosts in the distance. I open my eyes again, and we pass a small patch of dense forest (or at least what passes for forest in Denmark). My mind wanders and I reflect on what I see. Denmark is a small country and the land, including the forests, is heavily managed, so the diversity of life isn't terribly high. You could to go the rain forests of Costa Rica or Brazil and be far more impressed with the tropical birds, frogs, insects, and the abundant greenery. Still, even in Denmark, the landscape is brilliant green and teeming with life. Indeed, no matter how you look at it, Earth is defined by abundant and diverse life. The question that preoccupies me now is why?

One might suggest that all the life we see is simply a consequence of a long history of biological evolution on Earth. In his wonderful book *Life on a Young Planet*, my colleague and good friend Andy Knoll from

Harvard University documents the changing face of life during the first four billion years of Earth history. He shows how a variety of biological innovations, like the invention of oxygen-producing photosynthesis, for example, fundamentally shaped the history of life. After oxygen-producing organisms first evolved, other organisms that use oxygen followed, and they then prospered, multiplied, and evolved into yet other oxygen-utilizing life forms. Eventually this led to animals, the most biologically complex of all organisms on Earth. With no oxygen, there would be no animals. So, clearly, innovations during biological evolution have shaped, evened defined, the biosphere. But does evolution alone explain the bounty of life on our planet?

To consider this question, we quickly compare Earth and Mars. Scientists still hold out for the possibility of life on Mars: after all, Mars is the same age as Earth and there is some evidence for at least occasional surface and subsurface water on the planet. Even as I write, NASA's rover *Curiosity* is probing the Martian surface for signs of water, and for clues as to how water interacts with the planet's surface environment. As we will discuss more fully below, and as the tenet goes, where there is water, there may be life. Yet, if there is life on Mars, it doesn't jump up and down like the Whos in Whoville, crying: "We are here, we are here, we are here!" In contrast, if intergalactic explorers probed Earth as we presently probe Mars, it would be impossible to miss Earth's abundant life. The question is, quite simply, why is there so much life on Earth?

To answer this we will for the moment abandon considerations of evolution and start with a more fundamental question: What are the basic ingredients needed for life, at least for life as we know it? As I digest my lunch of lasagna leftovers, I proclaim that food must be important. Yes indeed, but not all organisms can eat lasagna, and I'm reminded of a whole class of creatures who don't eat any kind of organic matter at all, but rather make their cells from simple inorganic substances. Plants fit this bill, growing from carbon dioxide and water and using the energy of the Sun to combine these compounds into cell biomass and oxygen.

Many other types of organisms also fit the bill, and most of them do not use the Sun for energy. Rather, they gain their energy from promoting the reaction between inorganic substances in so-called oxidation-reduction reactions, where electrons are transferred during the reaction.

To probe this idea further, let's think of salt. Put salt in water and it dissolves in a reaction that yields energy, but organisms cannot grow from the energy of this reaction; no electrons are transferred; and the chloride and sodium atoms have the same charge in the salt crystal as they do in the solution. Now think of cows. Cows house enormous populations of microbes in their digestive system, and many of them form methane. Many of these microbes, so-called methanogens, grow quite happily by combining hydrogen gas and carbon dioxide to form methane gas. No light is used, electrons are transferred, the methanogens are happy, and so, presumably, are the cows. Therefore, a basic necessity for life is energy, which is supplied either from light, or from a myriad of different oxidation-reduction reactions.[1] We will look at these issues in more detail in the next chapter, but for now, it's sufficient to highlight that energy is critical for life.

Energy is critical, but we need other things too. Cells are made up of carbon, oxygen, hydrogen, nitrogen, phosphorus, and sulfur as the major ingredients, with a whole suite of trace metals and other elements as well. All of these compounds are critical in the construction of basic cellular components like the cell membrane, genetic material (DNA and RNA), and all of the proteins and other molecules used in running the cell's machinery.

Another basic ingredient of life, at least for life as we know it, is a stable aqueous (meaning water) environment. Life likes it wet! Many organisms, of course, have evolved to live outside of the watery sphere of our planet, but they still all need water to live. So do we, but we just pack it inside our bodies. So, whether we're talking about desert cacti, spiders, snakes, trees, or the smallest bacteria, they all need water. Indeed, this is one reason, as mentioned above, why the search for life in our solar system and beyond is tantamount to searching for liquid water. "Wait," you might say, "I've heard about small bacteria and algae living in sea ice and even in glacial ice in some cases." Very true, but if the organism is alive and growing,[2] it has access to liquid water. In the case of sea ice, this could be brine channels formed as salt is excluded from the growing ice; or for glaciers, high pressure induces ice melting near the bottom, providing an aqueous environment for organisms. "Well then," you might add, "I've heard that the temperature record for a living organism is about 120°C (248°F), well above the boiling point of water at Earth's surface." True again, but these organisms are only found at high pressures, like deep in the ocean where the boiling point of water exceeds the upper temperature limit for life.

What is the big deal about water anyway? For one, water has special properties. Because of its physical structure, a water molecule is bipolar, which means that it is slightly charged with a positive charge on one side and a negative charge on the opposite side. This condition allows it to dissolve all kinds of so-called ionic chemical substances (also charged), many of which constitute the building blocks of life. These include nutrients like nitrate, ammonium, and phosphate, which form into critical components of DNA, RNA, and cell membranes, as well as a host of other substances including sulfate and a variety of trace metals, which help to build the biochemical machinery of the cell. Not only does water dissolve the substances, but these substances are also transported by diffusion and advection; and this movement provides a means by which they can be supplied to the cells. Water also provides the medium by which waste products can be exported from the cell.

The bipolar nature of water also allows for the formation of cell membranes. These separate the external environment from the inside of the cell where the business of life is conducted. Cell membranes are made up of special (phospholipid) molecules with one end containing water-loving chemical groups (hydrophilic) and the other end containing water-repelling chemical groups (hydrophobic). In forming a membrane, the water-loving side reaches out toward the water phase, while the water-repelling side reaches in and lies foot to foot with another row of water repelling bits whose water-loving sides reach out in the opposite direction. This lipid bilayer joins in a circle forming the cell membrane, separating the inside of the cell from the outside environment. All in all, from its ability to dissolved and transport the chemical constituents of life, to its ability to host membrane structures, water is a unique chemical substance.

Or maybe we're thinking too small, too Earthcentrically. Water is the fluid of life because its properties are perfect for the type of life that we know. Perhaps a different type of life could have evolved in different solvents with different properties. It's hard to rule this possibility out. Alternative potential solvents are sometimes named. These include ammonia, methane, sulfuric acid, or hydrogen fluoride (HF); at the right temperature and pressure, they share some (but not all) of the properties of water. Aside from numerous science fiction books and movies, there is also an active scientific literature on this fascinating topic. Discussions of life in these alternative solutions are, however, highly speculative; one might even say imaginative. Therefore, I'll take the easy road, and as far as we know for certain, water is the perfect and only solvent for life.

To summarize, we have highlighted three basic ingredients for life. These are energy, the chemical components that make up cells, and water. We will see that the availability of each of these is linked by special properties of planet Earth.

Let's start with water. It's no secret that Earth is a watery planet. From NASA's spell-binding images of our "blue planet" from space, to the "Rime of the Ancient Mariner" by Samuel Taylor Coleridge, we are reminded of the boundless expanse of the global oceans. We will not concern ourselves at length with why Earth has so much water—likely a combination of early degassing from its interior as well as delivery from comets—but rather with why the water we have is, well, wet. The answer of course is that most of the planet is of the right temperature, lying between the boiling and freezing points of water. But why? Here, at least in part, we are lucky. We can think of it like this. Earth sits at a certain distance from the Sun as dictated by its orbit. The Sun has a certain brightness as dictated by its size and chemical composition.

The amount of the Sun's warmth intercepted by Earth depends on a combination of these two factors. However, as all planets of our solar system are warmed by the same Sun, let's consider distance from the Sun as the key variable. It's easy to imagine that if Earth was closer to the Sun it would receive more warmth, and less warmth if further away. As it turns out, Earth resides at a distance from the Sun where the warmth is sufficient to allow liquid water to persist. If closer to the Sun like Venus, the temperature becomes too hot, and liquid water is boiled away into the atmosphere in a so-called runaway greenhouse. Some of this water may even be completely lost through chemical processes in the stratosphere. If further from the Sun, like Mars, the surface would become too cold and therefore frozen. The zone defining the optimal distance from the Sun (or any other star in fact) where liquid water can persist is known as the "habitable zone," which is sometimes referred to as the "Goldilocks Zone."[3]

But distance from the sun is only part of the story. Earth has an atmosphere with greenhouse gases that contribute to surface warming. Without any greenhouse warming, and with surface albedo as it is,[4] Earth would be frozen with a temperature of −15°C (5°F) or so. Therefore, discovering the habitable zone of a planet is more involved than described above. This requires some rather complex heat-budget calculations, which were first attempted decades ago; however, the most widely referred to models were presented in 1993 by Jim Kasting of Penn State University, along with his coworkers Daniel Whitmire and Ray Reynolds. Jim has been a leader in applying his detailed knowledge of atmospheric chemical dynamics to understanding the evolution of both Earth's atmosphere and atmospheres beyond our own. To attack the habitable zone issue Jim tried, through his model, to keep liquid water on the planet by changing atmospheric CO_2 (carbon dioxide) levels, as these control greenhouse warming. One can easily imagine that different atmospheric CO_2 levels would be needed to maintain a habitable zone in response to differences in solar luminosity, which is basically the intensity of a star; and differences in solar luminosity are expected as one travels either away from or toward the star, or in our case, the Sun.

With Jim's model, the outer reaches of the habitable zone are encountered when atmospheric CO_2 concentrations become so high that CO_2 clouds form. These clouds block solar radiation from reaching the planet surface and thereby increase planetary albedo. The end result is a frozen planet. There were other considerations in Jim's modeling that I won't get into here, but in the end, Jim and colleagues concluded that Mars probably lies just outside of the habitable zone. Likewise, Venus also lies outside of the habitable zone. In this case, solar luminosity is simply too high. Even with miniscule levels of atmospheric CO_2 supplying minimal greenhouse warming, the planet surface becomes so hot that water boils into the atmosphere. This situation generates a runaway greenhouse and very high surface temperatures because water is also a good greenhouse gas (and the most important on the modern Earth!).[5] By some of Jim's calculations, the inner edge of the habitable zone may

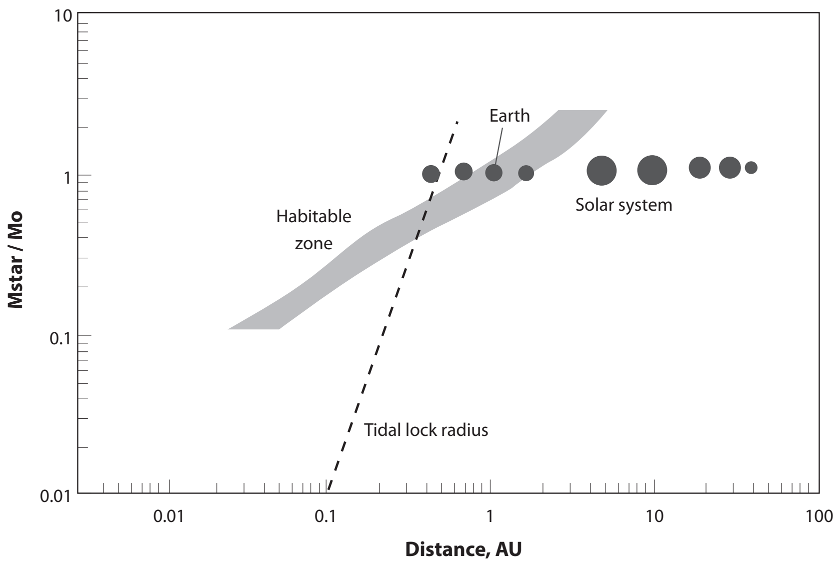

Figure 1.1. Habitability zone as determined by Jim Kasting and colleagues including the placement of the eight planets (plus Pluto) of our Solar System. One AU is one Earth distance from the Sun. The vertical axis shows the ratio between the mass of a star and the mass of the Sun. At distances less than the tidal lock radius from a star, planets become locked in rotations around their axis with small integer values relative to the time scale of the planet's orbit around the star (Mercury rotates 3 times on its axis for every 2 orbits around the Sun). In some cases a planet can orbit with a 1/1 rotation to orbit ratio, with the same side of the planet always facing the star. Planets within the habitable zone of small stars are within the tidal lock radius. From Kasting (2010).

lie as close as 95% of the distance from the Sun to Earth. This is about 4.5 million miles closer to the Sun than we are. The results of Jim's calculation are presented in figure 1.1, and by all accounts we are lucky; Earth sits snugly within the habitable zone of the Sun.

If this is true, why do we keep entertaining the possibility for life on Mars? Consistent with Jim's habitable zone arguments, there's no evidence for continuously standing surface water on Mars, at least not now. But during decades of satellite and surface exploration, including the recent, highly successful rovers, *Spirit* and *Opportunity* of the Mars Exploration Rover Mission (MER), and the THEMIS (high resolution thermal imaging system) imager onboard the Mars Odyssey orbiter, water has flowed and still does occasionally flow on Mars. This is evidenced by all sorts of channels, ditches, pools, and sedimentary rocks, whose formation is best explained by the action of water. Indeed, the *Curiosity* rover recently landed on the Mars surface and is, as I write, exploring the surroundings of its landing site, which appear to be an ancient river bed! All of this is in addition to spectroscopic observations of water just at and below the soil surface. So, Mars demonstrates that liquid water may be found, at least occasionally, somewhat outside of the habitable zone. By contrast with Earth, however, any life on Mars, if it exists at all, is not obvious and is seemingly restricted in its abundance and occurrence. Therefore, Mars does not and cannot support the magnitude of life that we find on our planet.

Buried in the discussion of Jim Kasting's habitable zone calculations is the idea that over long time scales, Earth actually regulates its own temperature. This idea was first raised by the cosmologist Carl Sagan. Sagan contributed greatly to our understanding of the composition of planetary atmospheres, and he helped frame the discussion about the search for life in the universe. He was an enormous inspiration to those interested in science through his PBS (Public Broadcasting System) program COSMOS, which was originally broadcast in 1980. However, of more importance here, he and his colleague George Mullen asked why Earth didn't freeze early in its history when the Sun was much less luminous than today.[6] Geological evidence points to the more or less continuous presence of liquid water for as far as back as 4.2 billion years ago. Yet, with the present abundance of greenhouse gases in Earth's atmosphere, the planet should have been frozen under the reduced luminosity of the early Sun. This is famously known as "The Faint Young Sun Paradox." Sagan and Mullen argued that this paradox could be solved with a high concentration of greenhouse gases like ammonia and methane; these gases are unstable in our present oxygenated atmosphere but could have been present in the oxygen-poor atmosphere of early Earth. It was soon pointed out, however, that ammonia would be photochemically unstable, even in an oxygen-free atmosphere. This generated a serious problem for the model. However, in a true intellectual quantum leap, Jim Walker, Paul Hays, and Jim Kasting recognized that CO_2 may well have been the greenhouse gas mitigating against an early frozen Earth. Okay, CO_2, big deal. But there is much more to this proposal, because Walker, Hays and Kasting also demonstrated a mechanism that actually regulates surface temperature.

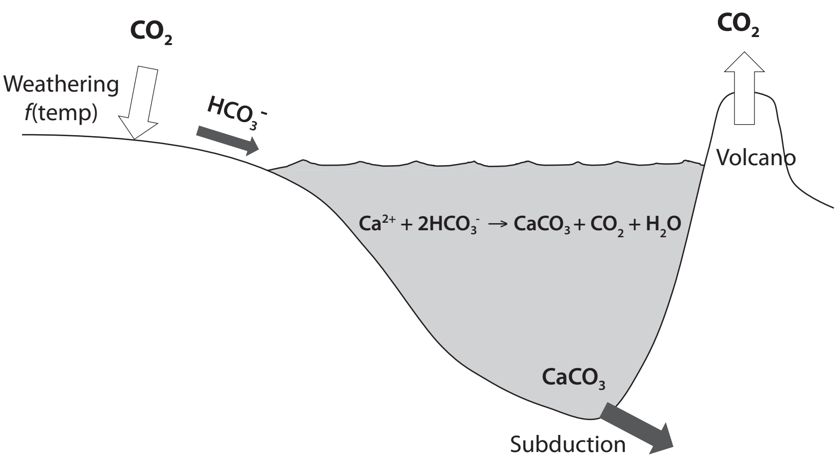

Figure 1.2. The carbon cycle as it acts to regulate Earth's surface temperature. Redrawn from Kasting (2010).

The logic goes like this. Carbon dioxide is constantly introduced from the interior of Earth into the atmosphere. The CO_2 comes from volcanoes and from hydrothermal vents at the bottom of the ocean. However, if we look carefully, we see that these CO_2 sources, at least most of them, originate as a result of Earth's continuous churning in a process known as plate tectonics. In practice, the loss of heat from Earth's interior (estimated at some 5000°C in the middle) causes the mantle (the layer just below Earth's crust) to move and mix in a process known as convection. This convection creates regions of volcanic outpourings, mostly into the oceans, that divide Earth's crust into a series of mobile plates riding on the mantle below. As new ocean floor is formed by this process, old ocean floor is also injected back into the mantle in a process known as subduction (see fig. 1.2). This is a violent process generating most of the major earthquakes, and it is a prime builder of mountain ranges. So, CO_2 is liberated to the atmosphere, but it doesn't accumulate forever. Indeed, it is actively removed by a process known as chemical weathering, where the CO_2 reacts with rocks at Earth's surface.[7] A particularly interesting aspect of weathering is that it is temperature sensitive; it goes faster at higher temperatures.

With this in mind, we can start to imagine how planetary-scale temperature regulation might work. If atmospheric temperature gets too high for some reason, the weathering rate will increase, and CO_2 will be more actively removed from the atmosphere. The increased removal of CO_2 will in turn cause the CO_2 concentration in the atmosphere to drop, reduce the greenhouse warming, and as a result, the temperature will drop. Therefore, a balance point is reached between CO_2 concentration, temperature, and the removal rate of CO_2 by weathering. Suppose for some reason Earth becomes completely frozen. This may have happened a few times during the course of Earth's history. If so, we need not worry, at least when considering long geologic time scales. Tectonic processes ensure that CO_2 will continuously be added to the atmosphere. Without liquid water, there will be no CO_2 removal by weathering, so the CO_2 concentration will build up until temperatures rise to the point where ice melts, and weathering commences again.

During weathering, CO_2 is converted to a soluble ion known as bicarbonate (HCO_3^-), which precipitates as minerals like calcite and dolomite (think of clam shells and coral reefs) in the oceans. These minerals are decomposed back to CO_2 during the subduction processes, thus completing the cycle. To summarize then, Earth, through the cycling of rocks (also known as the rock cycle), has an active control mechanism for temperature, which is enabled by the churnings of the mantle and the associated process of plate tectonics. Therefore, plate tectonics is also critical in allowing Earth to enjoy a continuous record of water through most of its long history.

This is a beautiful story, but is it true? I think that it must be, at least in its broad detail. Some geological evidence, however, points to early-Earth concentrations of atmospheric CO_2 that were too low to warm an Earth illuminated by a less powerful Sun.[8] Jim Kasting has again stepped into the discussion by suggesting that methane may have been, harking back to Sagan and Mullen, a major greenhouse gas early in Earth history. This would help explain the low CO_2 concentrations.[9] This may also be true, but the methane cycle does not obviously lend itself to robust temperature control like CO_2. Very recently, Minik Rosing and colleagues (we meet Minik again in chapter 7) argued that maybe we've been thinking about the problem incorrectly. They suggest, in fact, that maybe the albedo of early Earth was much lower than today,[10] so perhaps we didn't need as much greenhouse gas to warm the planet. Jim Kasting isn't terribly happy with this idea, but lower concentrations of atmospheric CO_2 can satisfy both the geological evidence for ancient CO_2 levels and produce enough of a greenhouse effect to warm the planet in the presence of a faint young Sun. Therefore, the CO_2 control mechanism as originally described by Walker and Kasting can still work to regulate Earth's temperature through time, even if ancient CO_2 levels were lower than we once thought.

Now back to the original question. It's one thing to have water, but it's another thing to support an abundant biosphere. As mentioned in the beginning of this chapter, life is nearly everywhere on Earth's surface. But how does our planet support it? Let's try some calculations. Photosynthetic life on Earth, working at present rates of photosynthesis, would deplete all of the CO_2 in the atmosphere in nine years.[11] Likewise, photosynthetic life in the oceans would deplete all of the available phosphorus, a key nutrient in making aquatic plants and algae, in just 86 years.[12] If this is true, how can we support so much life over long time scales? Part of the answer is that most of the CO_2 and nutrients tied up in plants and algae are liberated back to the environment as these organisms die and are consumed and decomposed by all manner of creatures from giant pandas to bacteria. Okay, but still some plant material and phosphorus aren't liberated back to the environment, and instead these things get buried in sediments and formed into rock. If we redo our calculations based on these rates of loss, we find that CO_2 would be depleted in 13,000 years,[13] and phosphorus in 29,000 years. These are still pretty short time scales compared to the billions of years that life has existed on the planet and the hundreds of millions of years that plants and animals have populated the land surface. How do we explain this?

The answer is actually quite simple. We appeal to the same tectonic processes we used to explain the role of CO_2 in solving the faint young Sun paradox. Luckily, when materials are sequestered into marine sediments on Earth, they are not permanently trapped there. The tectonic movements of the planet ensure that they are not. Through the processes of subduction, mountain building, and sea-level change (sea level is influenced by both tectonics and climate) most of these materials will be exposed again to the weathering environment. During weathering, organic matter is turned back to CO_2, phosphorus is liberated again to solution, and a whole host of other ingredients for life become available once more to support the growth of organisms. The key here is that the magnitude of life we enjoy on Earth is possible because of the active recycling of life's constituents by tectonic processes. This was first recognized over two hundred years ago by James Hutton, whom we also met in the Preface. He wrote the following in his treatise *Theory of the Earth* (1788):

> The end of nature in placing an internal fire or power of heat, and a force of irresistible expansion, in the body of this Earth, is to consolidate the sediment collected at the bottom of the sea, and to form thereof a mass of permanent land above the level of the ocean for the maintainment of plants and animals.

Finally, what about energy? I will say much more about energy in the next chapter, particularly about the types of energy needed for life, many of which you normally wouldn't think about. On modern Earth though, most (probably over 99%) of the energy to the biosphere ultimately comes from the Sun, driving the photosynthesis of plants, algae, and microbes (known as cyanobacteria; we will hear much more about them in later chapters) that produce organic material and oxygen. These products of photosynthesis are biologically recombined in Earth's great food chains. For example, copepods in the ocean eat algae, small fish eat the copepods, larger fish eat the small fish, and even larger fish eat these. These fish die and are decomposed by a variety of bacteria, which in turn are consumed by other organisms. The chain goes on and on but it is fueled, ultimately, by the organic matter and oxygen produced by photosynthesis. As described above, however, the organisms producing the oxygen, and driving the biosphere, obtain their building blocks from material recycled through plate tectonics. Thus, while the Sun supplies the energy, the rates at which tectonics recycles basic biological components sets the tempo.

All in all, we must agree that Earth is a pretty terrific place for life. It sits comfortably within the habitable zone of the Sun. In addition, its active tectonics both control the temperature of the surface environment, providing a continuous supply of liquid water, and recycle the basic components required to fuel abundant life. As we will see in the next chapter, the same tectonics may have also provided optimal conditions for the earliest biosphere.

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Note: Page numbers in italic type indicate illustrations.