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CHAPTER 1

OCEAN WORLDS ON EARTH AND BEYOND

If we have learned anything from life on Earth, it is that where you find liquid water, you generally find life. Water is essential to all life as we know it. It is the solvent, the watery broth that makes possible all the chemistry in our cells. Water dissolves many of the compounds that life, large and small, needs to grow and metabolize. Every living cell is a tiny bag of water in which the complex operations of life take place. Thus, as we search for life elsewhere in the solar system, we are primarily searching for places where liquid water can be found today or where it might have existed in the past.

The story of the search for life beyond Earth is, in part, the story of our planet, the pale blue dot,[1] reaching out into space, seeking signs of life on other worlds. Like a plant stretching vines out into its environment, our little planet has been sending its robotic emissaries out in spiral tendrils that circle other planets, probing for answers and sending back information.

We humans have been exploring our solar system with robotic vehicles for over 55 years. The first robotic mission to another planet was the flyby of Venus by the *Mariner 2* spacecraft on December 14, 1962. Since then, we have sent an armada of spacecraft to study the Sun and a variety of planets, moons, asteroids, and comets, most of which are in the inner reaches of our solar system. Over that same period, we have sent only eight spacecraft beyond the asteroid belt to study the many worlds in the outer reaches of the solar system.

Spacecraft that have gone beyond the asteroid belt—*Pioneer, Voyager, Galileo, Cassini, New Horizons, and Juno*—have revealed something profound about what it means for a world to be habitable. The data returned from those missions have served to revolutionize our understanding of where liquid water exists in our solar system, and by extension, where life might find a home.

We now have good reason to predict that at least six moons of the outer solar system likely harbor liquid water oceans beneath their icy crusts. These are oceans that exist today, and in several cases we have good reason to predict that they have been in existence for much of the history of the solar system. Three of these ocean worlds—Europa, Ganymede, and Callisto—orbit Jupiter. They are three of the four large moons first discovered in 1610 by Galileo. The fourth moon, Io, is the most volcanically active body in the solar system and does not have water. At least two more ocean worlds, Titan and Enceladus, orbit Saturn. Neptune's curious moon Triton, with an orbit opposite to the direction it rotates, also shows hints of an ocean below.

These are only the worlds for which we've been able to collect considerable data and evidence. Many more worlds could well harbor oceans. Pluto may hide a liquid mixture of water, ammonia, and methane, creating a bizarrely cold ocean of truly alien chemistry. The odd assembly of moons around Uranus—such as Ariel and Miranda—might also have subsurface oceans.

Finally, throughout the history of the solar system, ocean worlds may have come and gone; for example, the large asteroid Ceres likely had a liquid water ocean for much of its early history. Mars and Venus may also have had oceans previously. Early in our solar system's history, oceans might have been commonplace, be they on the surface of worlds like Venus, Earth, and Mars, or deep beneath icy crusts of worlds in the asteroid belt and beyond. Today, however, it is the outer solar system that harbors the most liquid water.

This distinction—between liquid water *in the past* and liquid water *in the present*—is important. If we really want to understand what makes any alien organism tick, then we need to find life that is alive today and that requires the presence and persistence of liquid water.

The molecules of life (e.g., DNA and RNA) don't last long in the rock record; they break down within thousands to millions of years, which, geologically speaking, is a short amount of time. Bones and other mineral structures of life can stick around much longer and form fossils. Fossils are great, but they only tell you so much about the organisms from which they formed.

As an example, Mars may have been very habitable roughly 3.5 billion years ago. Robotic vehicles, including the rovers *Spirit*, *Opportunity*, and *Curiosity*, have revealed that chemically rich lakes, and possibly vast oceans, populated the Martian surface. If life did arise within those liquid water environments, then some chemical or structural "fossils" might remain preserved within rocks from those ancient times. We would not, however, be able to extract any large molecules like DNA from those fossils. Our search for life on Mars is largely focused on scouring the rocks for any signs of ancient life that went extinct long ago.

Make no mistake, if we were to find rocks on Mars that showed signs of ancient life, it would be an extraordinary discovery. However, I would be left wanting more. I want to find life that is alive today, life that is *extant* as opposed to *extinct*.

This is important because I really want to understand *how life works*. What is the biochemistry that drives life on another world? On Earth, everything runs on DNA, RNA, ATP, and proteins. Darwinian evolution through natural selection has led to our amazing biosphere. The same fundamental biochemistry connects all of life's wild diversity. From the most extreme microbe to the craziest rock-and-roll star, we all have the DNA, RNA, ATP, and protein paradigm at our root. I want to know if there could be another way.

Can life work with some other fundamental biochemistry? Is it easy or hard for life to begin? Does the biochemistry of the origin of life converge toward DNA and RNA? Or were there contingencies that made these the best molecules for life on Earth but perhaps not on other worlds? If we were to find extant life in an ocean world, we could begin to truly answer these questions.

At an even higher level, consider the big picture of human knowledge.

When Galileo first turned his telescope toward the night sky and began charting the faint points of light he saw around Jupiter, he set in motion a revolution in physics. Night after night he drew Jupiter and the arrangement of these points of light. At first, he concluded that they must be stars that he could not see with the naked eye. He even named them the "stars of Medici" in honor of the Medici family since they were funding his research (Galileo was no idiot).

But through his diligent charting of these points of light, Galileo soon realized that they were not stars; they were moons orbiting Jupiter. His discovery got him into deep trouble with the Spanish Inquisition, and he ended up under house arrest. The idea that a celestial body would orbit anything other than the Earth was heretical. The world view at the time was framed around Aristotelian cosmology—the Earth is at the center of the universe and everything revolves around the Earth. Galileo's discovery put him at odds with this world view and provided strong evidence for the growing Copernican Revolution, the idea that the planets orbit the Sun and that the stars we see could well be suns with planets of their own.

In the decades that followed Galileo, advances in math and physics would lead to an appreciation that the laws of physics *work* beyond Earth. Gravity, energy, and momentum govern objects here on Earth as well as on worlds and wonders beyond.

In the century that followed these developments, the field of chemistry would grow and expand, eventually yielding instruments that could tell us the composition of the Sun, stars, and planets. The elements of the periodic table made up everything on Earth and beyond. Chemistry, too, works beyond Earth.

In the twentieth century, with the advent of the space age, our human and robotic explorers to the Moon, Venus, Mars, Mercury, and a host of asteroids would reveal that the principles of geology work beyond Earth. Rocks, minerals, mountains, and volcanoes populate our solar system and beyond.

But when it comes to biology, we have yet to make that leap. *Does biology work beyond Earth*? Does the phenomenon we know and love and call life *work* beyond Earth? It is the phenomenon that defines us, and yet we do not know whether it is a universal phenomenon. It is a simple but central question that lies at the heart of who we are, where we come from, and what kind of universe we live in.

Is biology an incredibly rare phenomenon, or does life arise wherever the conditions are right? Do we live in a biological universe?

We don't yet know. But for the first time in the history of humanity, we can do this great experiment. We have the tools and technology to explore and see whether life has taken hold within the distant oceans of our solar system.

SEARCHING FOR A SECOND ORIGIN

To answer these questions, we need to explore places where life could be alive today, and where the ingredients for life have had enough time to catalyze a second, independent origin of life.

This aspect of a second, independent origin is key. Take Mars again. Even if we were to find signs of life on Mars, there are limits to what we'd be able to conclude about that life form, and about life more generally. Mars and Earth are simply too close and too friendly, trading rocks since early childhood. When the solar system and planets were relatively young, large asteroids and comets bombarded Earth and Mars with regularity, scooping out craters and spraying ejecta into space. Some of this debris would have escaped Earth's gravity and may have ended up on a trajectory that eventually impacted Mars (or vice versa).

We know that life was abundant on Earth during many of these impact events, and thus it is not unreasonable to expect that some of the ejecta were vehicles for microbial hitchhikers—some few of which could (with a small probability) have survived the trip through space and the impact on Mars. Even if just a few microbes per rock survived, there were enough impacts and enough ejecta that the total number of Earth microbes delivered to Mars has been calculated to be in the range of tens of billions of cells over the history of the solar system. If one of those Earth rocks came careening through the Martian atmosphere about 3 billion years ago, it could have dropped into an ocean or lake on Mars, and any surviving microbes on board might have found themselves a nice new home on the red planet.

This possibility, however remote, would make it difficult to be completely confident that any life we discovered on Mars arose separately and independently—in other words, that it was really Martian. Life on Mars could be from Earth, and vice versa.

If we found fossils of microbes in ancient rocks on Mars, we would not be able to determine if that life used DNA or some other biochemistry. Lacking strong evidence for the more extraordinary claim of a second, independent origin of life on Mars, we would potentially have to conclude that Martian life came from Earth.

Indeed, even if we found extant life in the Martian surface or subsurface, there would still be significant potential for confusion as to where that life came from. Imagine that we found living microbes in the Martian permafrost or in some deep aquifer, and imagine even further that we discovered that those organisms also used DNA-based biochemistry. Even if we were unable to connect it to our tree of life, this shared biochemistry would force us to consider that Earth life and Martian life may have shared a common origin, whether life was transported from Earth to Mars or the other way around.

Although it's possible that such DNA-based life on Mars arose through convergent biochemical evolution, it would be hard to differentiate that scenario, and ultimately we would still not have conclusive evidence for a second origin. The only truly robust support for a second origin of life on Mars would be the discovery of extant life with a non-DNA-based biochemistry. Even then, there would still be a few scenarios to consider, and discard, that could implicate the Earth as the place of origin.

The ocean worlds of the outer solar system do not suffer these pitfalls. First, by focusing on worlds with liquid water oceans, we are focusing on worlds that could harbor extant life; and thus we could study their biochemistry in detail. Second, the "seeding problem" is almost negligible. Very few rocks ejected from the Earth could make it all the way to Jupiter and Saturn. In a computer simulation done by the planetary scientist Brett Gladman at the University of British Columbia, six million "rocks" were ejected from the Earth and sent on random, gravitationally determined trajectories around the Sun. Of those six million, only about a half dozen crashed into the surface of Europa. Slightly more make it onto the surface of Titan.

The rocks that do impact Europa do so at a speed that would cause them to vaporize on impact; none would be big enough to break a hole through Europa's ice shell. Therefore, any material that managed to survive the impact would be left on Europa's surface, exposed to harsh radiation. The energetic electrons and ions that pummel Europa's surface like rain from Jupiter's magnetic field would cook and kill any last surviving microbes.

In summary, it would be darn hard to seed Europa, or any of the ocean worlds of the outer solar system, with Earth life. Thus, even if we discovered DNA-based life there, we could reasonably conclude that those organisms represented a second, independent origin of life.

I should clarify that when it comes to looking for a separate, second origin of life and biochemistries that could be different from ours, I am not referring to what I call "weird life"—that is, life that does not use water as its primary solvent and carbon as its primary building block. We examine this topic in more detail when we explore Titan's surface, but for now, when I refer to "alternative biochemistries," I am still referring to water- and carbon-based life. What is "alternative" here is the prospect of finding different molecules that run the show, that is, an alternative to DNA.

In our efforts to see if biology works beyond Earth, we start with what we know works. Water- and carbon-based life *works* on Earth, and thus we look for similar environments beyond Earth.

But that is not to say that understanding the nature of water- and carbon-based life on Earth came easy. Earth's ocean has always been central to the story of life on Earth and how our planet balances ecosystems on a global scale. As Jacques-Yves Cousteau said at the beginning of his Ocean World book series, "The ocean is life." For millennia, the creatures of our ocean have populated our imaginations and guided our scientific pursuit of piecing together the tree of life on Earth.

OUR OWN ALIEN OCEAN

The story of the search for life beyond Earth is also the story of our growing understanding of our own oceans' depths, and our discovery of the secrets they hold. You may have seen old maps, maps where sea monsters, giant squid, and dragons dot the vast expanse of the seas yet to be explored. One globe from 1510 bears the phrase that has become synonymous with unknown dangers and risks: *Hic sunt dracones*; "Here be dragons."[2]

The ocean has long been the source of myths and legends. It was—and continues to be—home to aliens of a closer kind. How did we come to explore our own ocean and its many secrets?

The *Challenger* expedition, departing England December 1872 and returning home four years later, was the first to survey the biology of the deep ocean. The expedition's Royal Navy ship, the HMS *Challenger*, carried its crew around the world's oceans, covering a distance equivalent to a third of the way to our Moon. It was, and remains to this day, one of the most important and pioneering scientific expeditions to set sail.

Chief scientist of the expedition, Charles Wyville Thomson, was given permission from the Royal Navy to overhaul the ship, removing much of the weaponry on board and replacing it with instruments and labs. One instrument was little more than a fancy spool of line with a weight on the end. Simple as it was, this instrument would prove key to a great discovery.

In March 1875, the HMS *Challenger* was located southwest of Guam and dropped this line to a depth of 5.1 miles (8.2 km)—deeper than any line had been dropped into an ocean. Subsequent expeditions would reveal that the *Challenger* expedition had found the Earth's deepest ocean trench, the Mariana Trench, nearly 7 miles (11 km) at its deepest point.

The team on board the *Challenger* used nets and dredges to haul up whatever serendipity provided. Many of the creatures came up as gelatinous blobs, invertebrates whose form and function could be truly appreciated only in their native environment. The ethereal, alien beauty of a jellyfish, when hauled onto the deck of a ship, is reduced to colorless goo.

Long frustrated with their inability to directly observe creatures of the deep, explorers have worked throughout the ages to get firsthand access to the deep ocean. Diving bells were the original solution. If you have ever tipped over a canoe and swum underneath to breathe the air trapped by the canoe, you have experienced the basic operation of a diving bell. Imagine that a canoe has been weighted to sink to the bottom of a lake or river. The trapped pocket of air is the breathing space for anyone brave enough to take the trip down to the bottom.

According to paintings and reports, diving bell contraptions date as far back as Alexander the Great, a few centuries before the common era (BCE).[3] In a fun twist of the stars and seas, none other than Edmund Halley, discoverer of Halley's comet, innovated on the diving bell, creating a version in which the air could be cycled out and replaced with fresh air from the surface, carried by weighted canisters on a line.

In 1691, less than a decade after his observations of the comet that would come to bear his name, Halley and five colleagues descended in his diving bell to 60 feet (nearly 20 meters) in the River Thames. It was a small but significant step in getting humans deeper and opening our eyes to life in the depths.

The real leap in deep ocean exploration came in the late 1920s and early 1930s, when the engineering and science team of Otis Barton and William Beebe created and deployed their bathysphere—a hollow, steel sphere only 4 feet, 9 inches (1.5 meters) in diameter, with 3-inch-thick quartz windows. This sphere was connected to a cable on a ship's winch that could lower it down and haul it up. Electrical cables also enabled communication to the surface and provided power for lights.

In 1934 the pair of explorers—along with the support of their team from the New York Zoological Society, including naturalists Gloria Hollister and Jocelyn Crane, and engineer John Tee-Van—achieved their long-sought goal of reaching a depth of more than a half mile (nearly 1 km).

The team made many dives off the coast of Nonsuch Island in north Bermuda, and the creatures they saw filled catalogs of new and never-before-captured species. Beebe and the team were the first to study life in the deep ocean in its natural environment.

Beebe's description of a dive to 2,500 feet in early August 1934 captures his surreal experience: "There are certain nodes of emotion in a descent such as this, the first of which is the initial flash. This came at 670 feet, and it seemed to close a door upon the upper world. Green, the world-wide color of plants, had long since disappeared from our new cosmos, just as the last plants of the sea themselves had been left behind far overhead."[4]

On numerous occasions Beebe's writings and radio broadcasts linked the dark sea, peppered with bioluminescent creatures, to the twinkling stars of the night sky. After his successful dive with Barton to 3028 feet, Beebe wrote: "The only other place comparable to these marvelous nether regions, must surely be naked space itself, out far beyond atmosphere, between the stars, where sunlight has no grip upon the dust and rubbish of planetary air, where the blackness of space, the shining planets, comets, suns, and stars must really be closely akin to the world of life as it appears to the eyes of an awed human being, in the open ocean, one half mile down."[5]

The connection between sea and space appears time and again in exploration. Indeed, when NASA launched the first planetary spacecraft toward Venus in 1962, it was not given a name of astronomical significance but one that was connected to our ocean: *Mariner*.

And just two years before Mariner flew by Venus, humans themselves would make the plunge to the deepest part of the ocean for the first time, seven miles down in the Challenger Deep region of the Mariana Trench. In 1960 the *Trieste*, a 100-ton vehicle consisting of a sphere that fit two people (Jacques Piccard and Don Walsh) and a giant, buoyant carafe of gasoline, dropped to the deepest point in our ocean.

The dive of the *Trieste* bathyscaphe[6] marked what some hoped would be the beginning of an ambitious program to explore the deepest regions of our ocean. Designed by a Swiss inventor (Auguste Piccard, father of Jacques), built in its namesake region in Italy, and purchased by the United States Navy, it was the culmination of centuries of ocean exploration that sought to answer the question of what lies below not what lies above and beyond.

On that historic dive little was actually seen, as sediment that stirred up from the seafloor clouded much of the view, and Piccard and Walsh could not stay on the bottom for long. The deep ocean remained largely unseen.

But seventeen years after the *Trieste* landed in the Mariana Trench, in the spring of 1977, the abyss would give way to new insights into how life works in some of the most extreme environments on planet Earth. The veritable aliens within our own ocean would finally be revealed.

At that time, it was hard to imagine that there were still entire ecosystems on our planet yet to be discovered: the continents had been mapped; the poles had been reached; humans had touched down in the deepest point within Earth's ocean; the footprints of 12 humans even dotted the landscape of the Moon. What game-changing discoveries were left to be made?

Plenty, it turns out.

In that spring of 1977, a team of scientists set off to explore the Galápagos Rift, a region of the seafloor near the Galápagos Islands. They wanted to find out what was causing temperature anomalies in the region. Previous expeditions had measured these anomalies with instruments dropped down on cables and dragged around the ocean. The thinking at the time was that the plate tectonics of the spreading Galápagos Rift was creating a lot of localized heat; hot rocks were creating hot water, simple enough.

As part of the expedition, the team used *Alvin*, a US submersible, expecting to make important observations and discoveries about how geology works. But what they saw instead called into question how biology works.

At a depth of over 6,500 feet (2,000 meters), the lights on *Alvin* revealed structures that resembled tall and tortuous chimneys, billowing out "smoke" like active smelting plants from the Industrial Revolution. This was not smoke but clouds of fluids jetting out into the ocean at temperatures well beyond boiling—nearly 750 °F (400 °C). These fluids do not boil because they can't: the pressure is too high at those depths. These "superheated" fluids contain gases like hydrogen, methane, and hydrogen sulfide, as well as minerals that dissolve in the high-temperature and high-pressure fluids. The *Alvin* team had come across what we now call a hydrothermal vent—essentially a powerful, gushing hot spring at the bottom of the ocean.

The surprise was not so much the vents, but rather the bizarre and beautiful ecosystem surrounding the vent chimneys. Like a deep ocean version of animals congregating at a watering hole in the African savanna, the chimneys were host to never-before-seen creatures—red tube worms, stark white eel-like fish, and golden mounds of mussels—that were thriving in this extreme environment where conventional wisdom had said no animals should exist. And yet there they were.

How were these creatures surviving? What was sustaining this astonishing ecosystem?

On the surface of the Earth, the base of the food chain is driven by photosynthesis. Algae and plants harness the Sun's energy, breathing in carbon dioxide, extracting the carbon to build the structures of life, and then exhaling oxygen. Small organisms and animals eat the photosynthetic organisms, and then larger organisms eat those, and so on.

At the bottom of the ocean, however, the Sun is nowhere to be seen, and the food chain as we know it breaks down. Light from the Sun penetrates about 1,000 feet (300 meters) down, but beyond that, photosynthesis is not an option.

What was the base of the food chain at these hydrothermal vents? This is where the chemistry of the vents come in to play, offering essential nutrients and forming oases for life on the seafloor. The vents erupt hydrogen, methane, hydrogen sulfide, and a host of metals, many of which turn out to be tasty treats for microbes. The microbes utilize chemosynthesis instead of photosynthesis. Here the prefix "chemo" denotes that the microbes are synthesizing what they need for life with chemicals from the chimneys instead of photons from the Sun.

Chemosynthesis forms the base of the food chain at the vents. Microbes survive off the fluids and gases from the hydrothermal vents, and then larger organisms eat them, followed by larger creatures that eat those organisms, and so on. In some cases, the larger organisms were found to have also developed symbiotic relationships with the microbes—hosting the microbes within their bodies in exchange for the microbes detoxifying the water. All in all, a new and very surprising type of ecosystem had been discovered on that historic dive to the Galápagos Rift in 1977.

Life—large and small—was found to thrive in a region where most would have said it was not possible.

Only two years later, in March and July 1979, twin *Voyager* spacecraft would fly past Jupiter, capturing the first close-up images of Europa and Jupiter's other large moons. Those images would lay the foundation for thinking there might exist oceans of liquid water in a region where most would have said it was not possible.

In those brief years of the late 1970s, two seemingly disparate but phenomenal discoveries helped pave the way for a new approach to the search for life beyond Earth. The prospect of a liquid water ocean within Europa was all the more exciting once it became clear, through the discovery of the hydrothermal vents, that life could thrive in the dark regions of our ocean, cut off from the Sun, in a manner perhaps similar to that of an ice-covered ocean.

Our own alien ocean, hidden in the abyss, provided a glimmer of hope that distant oceans beyond Earth might also harbor life. In the chapters ahead, we dive deep into how we think we know these oceans beyond Earth exist and why we think they could be habitable. But first, we need to understand the sweet spot for habitability and why some of these ice-covered moons might reside in that sweet spot. To develop that understanding, we begin with the classic story of Goldilocks.

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