THE UNIVERSE WITHIN

DISCOVERING THE COMMON HISTORY OF ROCKS, PLANETS, AND PEOPLE

NEIL SHUBIN

AUTHOR OF *YOUR INNER FISH*

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PROLOGUE

Having spent the better part of my working life staring at rocks on the ground, I've gained a certain perspective on life and the universe. My professional aspiration—uncovering clues to the making of our bodies—lies inside the baked desert floor or deep within the frozen Arctic. While this ambition may seem eccentric, it is not much different from that of colleagues who peer at the light of distant stars and galaxies, map the bottom of the oceans, or chart the surface of barren planets in our solar system. What weaves our work together are some of the most powerful ideas that mankind has ever developed, ones that can explain how we and our world came to be.

These notions inspired my first book, *Your Inner Fish*. Inside every organ, cell, and piece of DNA in our bodies lie over 3.5 billion years of the history of life. Accordingly, clues to the human story reside within impressions of worms in rock, the DNA of fish, and clumps of algae in a pond.

While I was thinking about that book, it became clear that worms, fish, and algae are but gateways to ever deeper connections—ones that extend back billions of years before the presence of life and of Earth itself. Written inside us is the birth of the stars, the movement of heavenly bodies across the sky, even the origin of days themselves.

During the past 13.7 billion years (or so), the universe came about in the big bang, stars have formed and died, and our planet congealed from matter in space. In the eons since, Earth has circled the sun while mountains, seas, and whole continents have come and gone.

Discovery after discovery in the past century has confirmed the multibillion-year age of Earth, the sheer vastness of the cosmos, and our species' humble position in the tree of life on our planet. Against this backdrop, you could legitimately wonder if it is part of the job description of scientists to make people feel utterly puny and insignificant in the face of the enormity of space and time.

But by smashing the smallest atoms and surveying the largest galaxies, exploring rocks on the highest mountains and in the deepest seas, and coming to terms with the DNA inside every species alive today, we uncover a sublimely beautiful truth. Within each of us lie some of the most profound stories of all.

THE UNIVERSE WITHIN

CHAPTER ONE

ROCKING OUR WORLD

Viewed from the sky, my companion and I must have looked like two black specks perched high on a vast plain of rock, snow, and ice. It was the end of a long trek, and we were slogging our way back to camp on a ridge sandwiched between two of the greatest ice sheets on the planet. The clear northern sky opened a panorama that swept from the pack ice of the Arctic Ocean in the east to the seemingly boundless Greenland ice cap to our west. After a productive day prospecting for fossils and an exhilarating hike, and with the majestic vista around us, we felt as if we were walking on top of the world.

Our reverie was abruptly cut short by a change in the rocks beneath our feet. As we traversed the bedrock, brown sandstones gave way to ledges of pink limestone that, from our earlier discoveries, became an auspicious sign that fossils were in the neighborhood. After we spent a few minutes peering at boulders, alarm bells went off; my attention was pulled to an unusual glimmer flashing from a corner of a melon-sized rock. Experience in the field taught me to respect the sensation triggered by these moments. We had traveled to Greenland to hunt for small fossils, so I hunched over my magnifying lens to scan the rock closely. The sparkle that arrested me sprang from a little white spot, no bigger than a sesame seed. I spent the better part of five minutes curled up with the rock close to my eyes before passing it to my colleague Farish for his expert opinion.

Concentrating attention on the fleck with his lens, Farish froze solid. His eyes shot back to me with a look of pent-up emotion, disbelief, and surprise. Rising from his crouch, he took off his gloves and launched them about twenty feet in the air. Then he nearly crushed me with one of the most titanic bear hugs I have ever received.

Farish's exuberance made me forget the near absurdity of feeling excitement at finding a tooth not much bigger than a grain of sand. We found what we had spent three years, countless dollars, and many sprained ligaments looking for: a 200-million-year-old link between reptiles and mammals. But this project was no miniature trophy hunt. The little tooth represents one of our own links to worlds long gone. Hidden inside these Greenlandic rocks lie our deep ties to the forces that shaped our bodies, the planet, even the entire universe.

Seeing our connections to the natural world is like detecting the pattern hidden inside an optical illusion. We encounter bodies, rocks, and stars every day of our lives. Train the eye, and these familiar entities give way to deeper realities. When you learn to view the world through this lens, bodies and stars become windows to a past that was vast almost beyond comprehension, occasionally catastrophic, and always shared among living things and the universe that fostered them.

How does such a big world lie inside this tiny tooth, let alone inside our bodies? The story starts with how we ended up on that frozen Greenlandic ridge in the first place.

Imagine arriving at a vista that extends as far as the eye can see, knowing you are looking inside it for a fossil the size of the period that ends this sentence. If fossil bones can be small, so too are whole vistas relative to the surface area of Earth. Knowing how to find past life means learning to see rocks not as static objects but as entities with a dynamic and often violent history. It also means understanding that our bodies, as well as our entire world, represent just moments in time.

The playbook that fossil hunters use to develop new places to look has been pretty much unchanged for the past 150 years. Intellectually, it is as simple as it gets: find places on the planet that have rocks of the right age to answer whatever question interests you, rocks of the type likely to hold fossils, and rocks exposed on the surface. The less you have to dig, the better. This approach, which I described in *Your Inner Fish,* led me and my colleagues, in 2004, to find a fish at the cusp of the transition to life on land.

As a student in the early 1980s, I gravitated to a team that had developed tools to make headway finding new places to hunt fossils. Their goal was to uncover the earliest relatives of mammals in the fossil record. The group had found small shrewlike fossils and their reptilian cousins in a number of places in the American West, but by the mid-1980s their success had brought them to an impasse. The problem is best captured by the jest "Each newly discovered missing link creates two new gaps in the fossil record." They had done their share of creating gaps and were now left with one in rocks about 200 million years old.

The search for fossil sites is aided by economics and politics. With the potential for significant oil, gas, and mineral discoveries, there are incentives for countries to catalog and map the geology exposed inside their borders. Consequently, virtually any geological library holds journal articles, reports, and, one hopes, maps detailing the age, structure, and mineral content of the rocks exposed on the surface of different regions. The challenge is to find the right maps.

Professor Farish A. Jenkins Jr. led the team at Harvard's Museum of Comparative Zoology. Fossil discovery was the coin of the realm for him and his crew, and it started in the library.

Farish's laboratory colleagues Chuck Schaff and Bill Amaral were key in this effort; they had honed their understanding of geology to predict likely places to make discoveries, and, importantly, they trained their eyes to find really small fossils. Their relationship often took the form of a long, friendly argument: one would propose a new idea while the other would relentlessly try to quash it. If the idea held up under their largely amiable tit for tat, then they would both line up behind the proposal and take it to Farish, with his keen logistic and scientific sense, for vetting.

One day in 1986, while chewing the fat with Chuck, Bill found a copy of the *Shell Oil Guide to the Permian and Triassic of the World* on Chuck's desk. Paging through the volume, Bill spotted a map of Greenland, with a little hatched area of Triassic rocks on the eastern coast at a latitude of about 72 degrees north, roughly that of the northernmost tip of Alaska. Bill kicked things off by proclaiming that this could be a prime next area to work. The usual argument ensued, with Chuck denying that the rocks were the right type, Bill responding, and Chuck countering.

By dumb luck, Chuck had the means to end the debate right on his bookshelf. A few weeks earlier, he was trolling through the library discards and pulled out a paper titled "Revision of Triassic Stratigraphy of the Scoresby Land and Jameson Land Region, East Greenland," authored by a team of Danish geologists in the 1970s. Little did anyone know at the time, but this freebie, saved from the trash heap, was to loom large in our lives for the next ten years. Virtually from the minute Bill and Chuck looked at the maps in the reprint, the debate was over.

My graduate student office was down the hall, and as was typical for that time in the late afternoon, I swung by Chuck's office to see what was what. Bill was hovering about, and it was clear that some residue from one of their debates remained in the air. Bill didn't say much; he just slapped Chuck's geological reprint down in front of me. In it was a map that showed exactly what we had hoped for. Exposed on the eastern coast of Greenland, across the ocean from Iceland, were the perfect kinds of rocks in which to find early mammals, dinosaurs, and other scientific goodies.

The maps looked exotic, even ominous. The east coast of Greenland is remote and mountainous. And the names evoke explorers of the past: Jameson Land, Scoresby Land, and Wegener Halvø. It didn't help matters that I knew that a number of explorers had perished during their trips there.

Fortunately, the expeditions that transpired ultimately rested on Farish's, Bill's, and Chuck's shoulders. With about sixty years of fieldwork between them, they had developed a deep reservoir of hard-earned knowledge about working in different kinds of field conditions. Of course, few experiences could have prepared us for this one. As a famed expedition leader once told me, "There is nothing like your first trip to the Arctic."

I learned plenty of lessons that first year in Greenland, ones that were to become useful when I began running my own Arctic expeditions eleven years later. By bringing leaky leather boots, a small used tent, and a huge flashlight to the land of mud, ice, and the midnight sun, I made so many bad choices that first year that I remained smiling only by reciting my own motto, "Never do anything for the first time."

The most nerve-racking moment of that inaugural trip came when selecting the initial base camp, a decision made in a fleeting moment while flying in a helicopter. As the rotors turn, money flies out the window, because the costs of Arctic helicopters can be as high as three thousand dollars per hour. On a paleontology budget, geared more to beat-up pickups than to Bell 212 Twin Hueys, that means wasting no time. Once over a promising site revealed by the maps back in the laboratory, we rapidly check off a number of important properties before setting down. We need to find a patch of ground that is dry and flat yet still close to water for our daily camp needs, far enough inland so that polar bears aren't a problem, shielded from the wind, and near exposures of rock to study.

The Greenland crew clockwise from top left: Farish, military trim; Chuck, wise fossil finder; Bill, man who makes things happen in the field; and me. I made a lot of bad choices that first year (note hat).

We had a good idea of the general area from the maps and aerial photographs, and ended up setting down on a beautiful little patch of tundra in the middle of a wide valley. There were creeks from which we could draw water. The place was flat and dry, so we could pitch our tents securely. It even had a gorgeous view of a snowy mountain range and glacier on the eastern end of the valley. But we would soon discover a major shortcoming. There were no decent rocks within easy walking distance.

Once camp was established to our satisfaction, we set off each day with one goal in mind: to find the rocks. We'd climb the highest elevations near camp and scan the distance with binoculars for any of the exposures that figured so prominently in the paper Bill and Chuck had found. Our search was eased by the fact that the rock layers were collectively known as red beds for their characteristic hue.

With red rock on our minds, we went off in teams, Chuck and Farish climbing hills to give them views of the southern rocks, Bill and I setting off for places that would reveal those to the north. Three days into the hunt, both teams returned with the same news. Out in the distance, about six miles away to the northeast, was a sliver of red. We'd argue about this little outcrop of rock, scoping it with our binoculars at every opportunity for the remainder of the week. Some days, when the light was right, it seemed to be a series of ridges ideal for fossil work.

It was decided that Bill and I would scout a trail to get to the rocks. Since I didn't know how to walk in the Arctic, and had made an unfortunate boot selection, the trek turned out to be an ordeal—first through boulder fields, then across small glaciers, and pretty much through mud for the rest of the way. The mud formed from wet clay that made an indelicate *glurp* as we extricated our feet from each step. No footprint remained, only a jiggling viscous mass.

In three days of testing routes, we plotted a viable course to the promising rocks. After a four-hour hike, the red sliver in our binocular view from camp turned out to be a series of cliffs, ridges, and hillocks of the exact kind of rock we needed. With any luck, bones would be weathering out of the rock's surface.

The goal now became to return with Farish and Chuck, doing the hike as fast as possible to leave enough time to hunt for bones before having to turn back home. Arriving with the whole crew, Bill and I felt like proud homeowners showing off our property. Farish and Chuck, tired from the hike but excited about the prospect of finding fossils, were in no mood to chat. They swiftly got into the paleontological rhythm of walking the rocks at a slow pace, eyes on the ground, methodically scanning for bone at the surface.

Bill and I set off for a ridge about half a mile away that would give us a view of what awaited us even farther north. After a small break, Bill started to scan the landscape for anything of interest: our colleagues, polar bears, other wildlife. He stopped scanning and said, "Chuck's down." Training my binoculars on his object, I could see Chuck was indeed on his hands and knees methodically crawling on the rock. To a paleontologist this meant one thing: Chuck was picking up fossil bones.

Our short amble to Chuck confirmed the promise of the binocular scan; he had indeed found a small piece of bone. But our hike to this little spot had taken four hours, and we now had to head back. We set off, with Farish, Bill, Chuck, and me in a line about thirty feet apart. After about a quarter of a mile something on the ground caught my eye. It had a sheen that I'd seen before. Dropping to my knees like Chuck an hour earlier, I saw it in its full glory, a hunk of bone the size of my fist. To the left was more bone, to the right even more. I called to Farish, Bill, and Chuck. No response. Looking up, I knew why. They were also on their hands and knees. We were all crawling in the same colossal field of broken bones.

At summer's end, we returned boxes of these fossil bones to the lab, where Bill put them together like a three-dimensional jigsaw puzzle. The creature was about twenty feet long, with a series of flat leaf-shaped teeth, a long neck, and a small head. The beast had the diagnostic limb anatomy of a dinosaur, albeit a relatively small one.

This kind of dinosaur, known as a prosauropod, holds an important place in North American paleontology. Dinosaurs in eastern North America were originally discovered along streams, railroad lines, and roads, the only places with decent exposures of rocks. The eminent Yale paleontologist Richard Swann Lull (1867–1957) found a prosauropod in a rock quarry in Manchester, Connecticut. The only problem was that it was the back end. The block containing the front end, he was chagrined to learn, had earlier been incorporated into the abutment of a bridge in the town of South Manchester. Undeterred, Lull described the dinosaur from its rear end only. When the bridge was demolished in 1969, the other fragments came to light. Who knows what fossil dinosaurs remain to be discovered deep inside Manhattan? The island's famous brownstone town houses are made of this same kind of sandstone.

The hills in Greenland form large staircases of rock that not only break boots but also tell the story of the stones' origins. Hard layers of sandstones, almost as resistant as concrete, poke out from softer ones that weather away more quickly. Virtually identical staircases lie farther south; matching sandstones, siltstones, and shales extend from North Carolina to Connecticut all the way to Greenland. These layers have a distinctive signature of faults and sediment. They speak of places where lakes sat inside steep valleys that formed as the earth fractured apart. The pattern of ancient faults, volcanoes, and lake beds in these rocks is almost identical to the great rift lakes in Africa today—Lake Victoria and Lake Malawi—where movements inside Earth cause the surface to split and separate, leaving a gaping basin filled by the water of lakes and streams. In the past, rifts like these extended all the way up the coast of North America.

From the beginning, our whole plan was to follow the trail of the rifts. Knowing that the rocks in eastern North America contained dinosaurs and small mammal-like creatures gave us the aha moment with Chuck's geological reprint. That, in turn, led us north to Greenland. Then, once in Greenland, we pursued

Greenlandic rocks are like one page in a vast library of volumes that contain the story of our world. Billions of years of history preceded that little tooth, and 200 million years have followed it. Through eons on Earth, seas have opened and closed, mountains have risen and eroded, and asteroids have come crashing down as the planet has coursed its way through the solar system. The layers of rock record era after era of changes to the climate, atmosphere, and crust of the planet itself. Transformation is the order of the day for the world: bodies grow and die, species emerge and go extinct, while every feature of our planetary and celestial home undergoes gradual change or episodes of catastrophic revolution.

Rocks and bodies are kinds of time capsules that carry the signature of great events that shaped them. The molecules that compose our bodies arose in stellar events in the distant origin of the solar system. Changes to Earth's atmosphere sculpted our cells and entire metabolic machinery. Pulses of mountain building, changes in orbits of the planet, and revolutions within Earth itself have had an impact on our bodies, minds, and the way we perceive the world around us.

Just like human bodies, this book is organized as a time line. We begin our story about 13.7 billion years ago, when the universe emerged in the big bang. Then we follow the history of our small corner of it to look at the consequences of the formation of the solar system, the moon, and the globe of Earth on the organs, cells, and genes inside each of us.

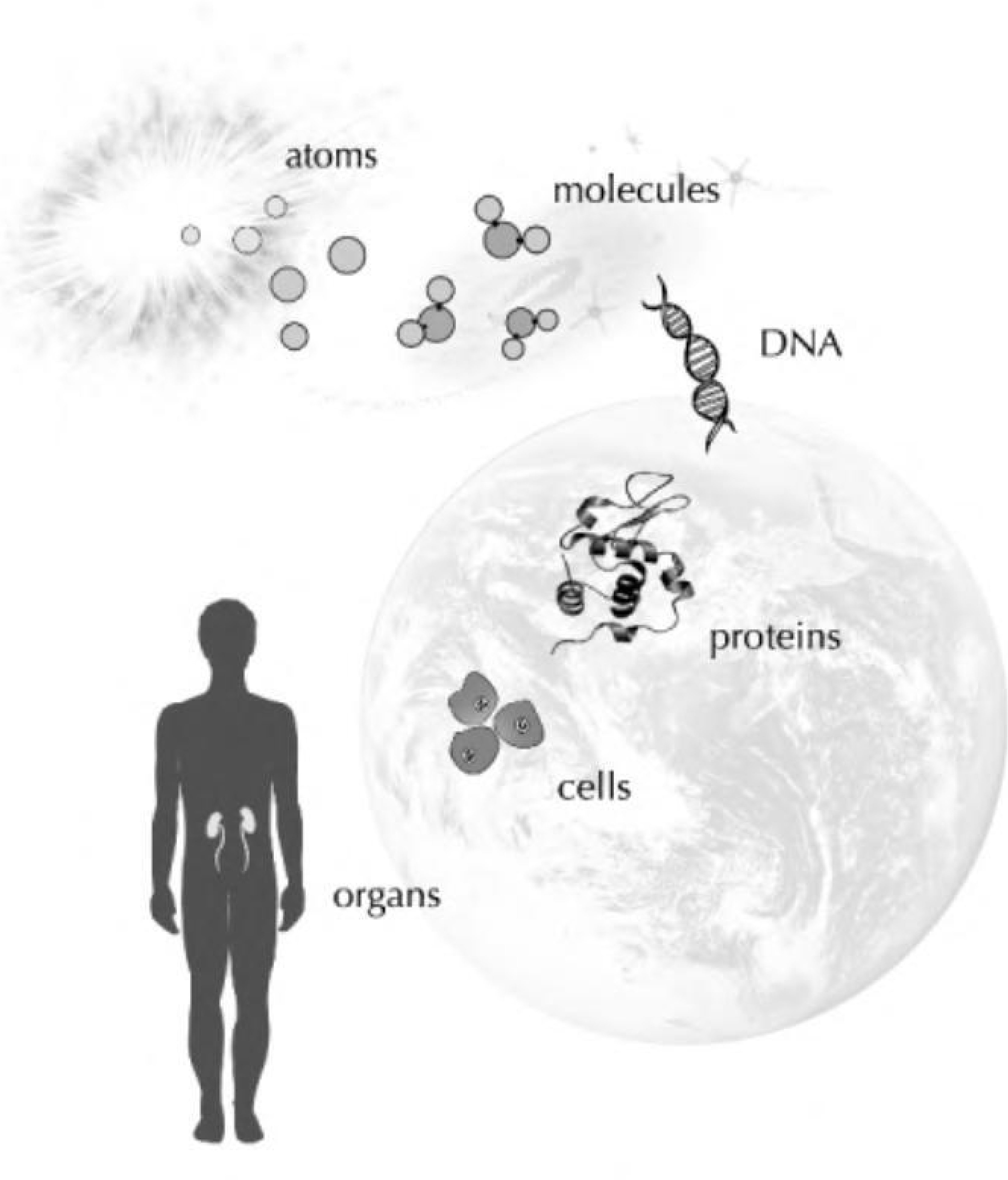
BLASTS FROM THE PAST

$H_{375,000,000}\ O_{132,000,000}\ C_{85,700,000}\ N_{6,430,000}\ Ca_{1,500,000}$
$P_{1,020,000}\ S_{206,000}\ Na_{183,000}\ K_{177,000}\ Cl_{127,000}\ Mg_{40,000}\ Si_{38,600}$
$Fe_{2,680}\ Zn_{2,110}\ Cu_{76}\ I_{14}\ Mn_{13}\ F_{13}\ Cr_{7}\ Se_{4}\ Mo_{3}\ Co_{1}$

is a formula of elements that make up the human body. We are a very select mix of atoms. Bodies are mostly hydrogen: for every atom of cobalt, for example, there are almost 400 million of hydrogen. By weight, we contain such a large amount of oxygen and carbon that we are virtually unique in the known universe.

One particular element missing from bodies tells a big story. Helium, the second-most abundant atom in the entire universe, has an internal structure that leaves it no room to trade electrons with others. Unable to make these exchanges, it cannot participate in the chemical reactions that define life—metabolism, reproduction, and growth. On the other hand, oxygen and carbon are about twenty times rarer than helium. But unlike helium, these atoms can easily interact with different elements to form the variety of chemical bonds that are essential in living matter. Reactivity is the order of the day for the common atoms of bodies. Loners need not apply.

The relative proportion of atoms is only a part of what defines our bodily structure. Bodies are organized like a set of Russian nesting dolls: tiny particles make atoms, groups of atoms make molecules, and molecules assemble and interact in different ways to compose our cells, tissues, and organs. Each level of organiza-



The Russian nesting dolls of all matter: tiny particles make atoms, atoms make molecules, and molecules make ever-larger entities.

tion brings new properties that are greater than the sum of its parts. You could know everything about each of the atoms inside your own liver, but that will not tell you how a liver works. Hierarchical architecture, smaller things making larger entities with new defining properties, is the basic way our world is organized and ultimately reveals our deepest connections to the universe, solar system, and planet.

Pick up a scientific journal in biology nowadays, and you stand a good chance of seeing a tree of relatedness. Every creature, from human to Thoroughbred to prize Hereford, has a pedigree—its family tree. These trees define how closely related living things are: first cousins are more closely related to one another than they are to second cousins. Knowing the pedigree becomes the basis for understanding how different creatures are connected to one another, how species came about, even why certain individuals may be more susceptible to disease than others. This is why doctors take family histories in medical exams.

A critical insight of modern biology is that our family history extends to all other living things. Unlocking this relationship means comparing different species with one another in a very precise way. An order to life is revealed in the features creatures have: closely related ones share more features with each other than do those more distantly related. A cow shares more organs and genes with people than it does with a fly: hair, warm-bloodedness, and mammary glands are shared by mammals and absent in insects. Until somebody finds a hairy fly with breasts, we would consider flies distant relatives to cows and people. Add a fish to this comparison, and we discover that fish are more closely related to cows and people than they are to flies. The reason is that fish, like people, have backbones, skulls, and appendages, all of which are lacking in flies. We can follow this logic to add species after species and find the family tree that relates people, fish, and flies to the millions of other species on the planet.

But why stop at living things?

The sun burns hydrogen. Other stars burn oxygen and carbon. The fundamental atoms that make our hands, feet, and brains serve as the fuel for stars. It isn't merely the atoms in our bodies that extend across the far reaches of the universe: molecules that make our bodies are found in space. The building blocks for the proteins and larger molecules that make us—amino acids and nitrates—rain down to Earth in meteorites and lie on the rocky crust of Mars or on the moons of Jupiter. If our chemical cousins are in the stars, meteors, and other heavenly bodies, then clues to our deepest connections to the universe must lie in the sky above our heads.

Detecting patterns in the sky—the shapes of galaxies, the features on planets, or the components of a binary star—is no easy task. Eyes take some time to adjust to the dark, but so too does perception. You need to train the eye to perceive faint patterns in the night sky. When it comes to deciphering fuzzy patches of stars through a telescope or binoculars, imagination and expectation have a way of conjuring mirages in the void. Removing these and actually seeing dim objects in space means emphasizing peripheral vision, the most sensitive light-gathering part of our eyes, to pick up faint light and discriminate fuzzy patches from one another. As we learn to see the sky, color, depth, and shape emerge in the world above our heads much like when a fossil bone pops into view on a dusty desert floor beneath our feet.

Discriminating celestial objects is merely the first step in learning to see the sky. Like a painting that has graced a house for generations, the stellar landscape we encounter today is much the same as that witnessed by our parents, grandparents, even our apelike ancestors. Generations of humans have not only seen the sky but, over time, built new ways of perceiving our connection to it.

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be estimated. With this insight, Henrietta Leavitt gave us a ruler with which to measure distances in deep space.

We have to imagine astronomy in that era to appreciate the transformative power of Leavitt's discovery. From the time of Galileo to Pickering, people observed the sky and saw the planets, nebulae, and fuzzy patches of light with ever-increasing clarity. But the central questions remained. How big is the universe? Is our own galaxy, the Milky Way, all there is?

No sooner had Leavitt proposed her idea in 1912 than other astronomers began to calibrate and apply it to the heavens. One Dutch scientist used Leavitt's ruler to measure the distances between individual stars. It gave him a big number. The galaxy is vast almost beyond imagination. Then Edwin Hubble, armed with Leavitt's idea, used the biggest telescope of the time to change our view of the universe almost overnight.

In 1918, Hubble, a Rhodes scholar and law student turned astronomer, deployed his enormous new Mount Wilson telescope to find one of the stars made famous by Leavitt. This star was special. It wasn't alone in the sky; it sat inside a cloud of gas, known as the Andromeda Nebula. When Hubble applied Leavitt's ruler to the star, he encountered a stunning fact: the star, in fact the whole nebula that contained it, was farther away from us than anything yet measured. The game changer came from the realization that this object was much more distant than any star in our own galaxy. This nebula was no cloud of gas; it was an entirely separate galaxy light-years from our own. With that observation, the Andromeda Nebula became the Andromeda Galaxy, and the world above our heads became vast and ancient almost beyond description.

Hubble, using the largest telescope of the day, mapped everything he could see with Leavitt's variable stars inside. The Andromeda and Milky Way Galaxies were only the tip of the iceberg. The heavens were filled with other galaxies composed of billions of stars. Many of the fuzzy patches of gas seen by observers for a century or more were really star clusters that lie far beyond our own galaxy. In a scientific age when people were grappling with the age of Earth, then thought to be on the order of 10 million to 100 million years old, the age and size of the universe revealed our planet to be just a minuscule speck in a vast universe composed of innumerable galaxies. These insights emerged as people learned to look at the sky in a new way.

Hubble applied another technique to measure objects in the sky. This one relied on an essential property of light. Light radiating from a source that is traveling toward us looks more blue than light traveling away, which looks more red. This color shift happens because light shares some features with waves. Individual waves emanating from a source moving closer to you will look more compressed than ones moving away. In the world of color, more closely spaced waves are on the blue end of the spectrum, more separated ones on the red. If Leavitt's technique was a ruler to measure distance in deep space, then the search for color shifts in light was a radar gun to measure speed.

With this tool, Hubble found a regularity: stars emit red-shifted light. This could mean only one thing. The objects in the heavens are moving away from us, and the universe itself is expanding. This expansion is not a pell-mell scatter; the heavens are scattering from a common center. Wind things back in time, and all the matter in the sky was at some distant time occupying a central point.

Not everybody liked this new idea; in fact, some experts hated it. Rival theories for the origin of the universe abounded. A proponent for one of them poked fun at Hubble's by giving it the moniker "big bang." Lacking in Hubble's theory, or in any other for that matter, was direct evidence in the form of a smoking gun.

The major breakthrough was an incidental by-product of people's need to communicate with one another. With technological innovations in wireless technology and expanding international commerce and collaboration in the late 1950s came a demand for