OXFORD

LIVING WITH THE STARS

How the human body is connected to the life cycles of the Earth, the planets, and the stars

KAREL SCHRIJVER & IRIS SCHRIJVER

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This dewdrop world
is but a dewdrop world,
and yet—

Kobayashi Issa (1763–1827)

Preface

Our journey to "get the big picture" of the physical place of the transient human body within the ecology of the universe and of the links between the atoms in our body and the lives of stars, resulted in the book that is now in front of you. This book rests on a foundation of many conversations in which we talked about a multitude of topics from our everyday professional lives as a physician focusing on the wonders of DNA married to an astrophysicist exploring the secrets of the Sun and other stars. The more we followed up on our questions to each other, the more we discovered that our apparently disjoint fields of professional interest had far more connections than we had imagined possible. Eventually, our naïve questions to each other began to shape a web of links so fascinating that we decided to integrate it all into a full story that we could share.

The numbers involved in tracing the connections are simply staggering. Appropriately enough, we can call the number of stars in the Galaxy—at least 100 billion (and likely a few times that many)—astronomically large. There are, however, something like 500 times that many cells in the average human body: 50 trillion (and maybe twice that many). Each cell, on average, contains very approximately as many atoms as there are cells in the body. We can but marvel at the human enterprise called science that is rapidly advancing our understanding of this vast hierarchy of scales. Similarly, we can but be in awe of our own bodies, which, most of the time, manage to successfully run an assembly of individual cells that outnumber the human population of the entire planet by a factor of close to 10,000.

Even more than the matters of scale and the variety of the links to the world around us, it was the utterly transient character of our human bodies that struck a chord. We are not just taking in and burning fuel, like a car would, but instead we use our food to rebuild our bodies, over and over again throughout our lives. Very little of our physical bodies lasts for more than a few years, which is completely at odds with our feelings of continuity over a lifetime. It is that transience of the body, and the flow of energy and matter needed to counter it, that led us to explore the interconnectedness of the universe.

The research for this book allowed us to merge our fields and to become, at least for a while, "astrophysicians" in search of the natural flow that inexorably ties our human experience to the universe at large: the growing of a plant in sunlight, distant exploding stars, the cycling of cells in the human body, and the Sun's influences on Earth all are parts of our daily existence, and their consequences are continually flowing through our bodies even if we do not realize it.

We invite you to take a journey with us as we tour the vast network of processes that link us to all life on Earth as much as to our Galaxy. Before reading this book, you might think that these associations are farfetched, but we hope to have created a story that convincingly makes the case for these connections. We hope that you will share our fascination with life on this large but isolated rock in the emptiness of interstellar space that makes such remarkably efficient use of the omnipresent building material: stardust.

You will see just how ephemeral and transient our existence is, and that throughout our lives our physical existence is continually recycled and rebuilt. We truly live by the grace of the stars, both by the Sun, which is our nearest stellar neighbor, and by the many generations of stars that came before.

In the first two chapters, we set the stage and describe just how transient our bodily form is, even as our person survives for decades. In Chapters 3, 4, and 5 we discuss the chemicals going into the making and remaking of our bodies. The connections of these chemicals to the world around us are the centerpieces of Chapters 6 through 11. How the ancient elements were formed and how they came to shape our solar system are at the core of Chapters 12 and 13. In a short, final chapter we review the connections between our bodies and the world around us, and the links between the many sciences needed to uncover them. Together, these chapters form a complete story, best read in order. They can, however, also be read by themselves, as essays focusing on particular sets of topics that are parts of the whole.

The birth of this book would not have been possible without the help of numerous individuals to whom we are forever indebted. We thank our parents, who stimulated us to look around and follow our dreams. We owe a debt of gratitude to the inventors and developers of the internet and the creators of Wikipedia, who, combined, enabled us to find and read texts from around the world, some of which are centuries old while others were recently conceived, from explorers and scientists,

including Nobel laureates and other giants of their times, and to the many scientists working in so many different fields on whose shoulders we all stand today to answer fascinating questions. So much information is literally at our fingertips in the search of knowledge. All we did was chase one link to another, find our way to where connections lay, and weave our story through it all. You will find no references in this text: the resources to which the internet gives you, the reader, access are so extensive that you should have no trouble at all looking up the original texts and background information going into this book and then some. We hope you will enjoy the incredible journey.

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If we are
stardust, if flecks of it glitter
in our bones,

is some part of the stars
our dust? Do bits
of the dead—the unwrapped,

unembalmed, unfettered
dead, those free of the trappings
of immortality—do they rise

seventeen times as high
as the moon? Has a strand
of someone's red hair

threaded its way through
Saturn's rings? Is dark matter
mottled, here and there,

with cells from a bright
blue eye? Do infinitesimal sperm
swim out of the Milky Way

and toward Andromeda? Suppose
some fragment of consciousness
managed to land on Mars—of course

it wouldn't matter, without a mouth,
an ear, without a soul
to tell its story to . . .

Sharon Bryan (1943–), excerpt from "Stardust"

1

The Illusion of Permanence

Our bodies are made of the burned-out embers of stars that were released into the Galaxy in massive explosions long before gravity pulled them together to form the Earth. These remnants now comprise essentially all the material in our bodies. Most of it has been cycling through the continents, with a small amount added only recently, when comets were captured by the Earth's gravity, or when ultrafast particles ran into the atmosphere and created a shower of new particles. It is being used by all living beings on the planet. Plants capture sunlight and release oxygen even as they create food for us, humans. We live by the grace of stardust assembled by plants into nutrients that provide us with energy to grow, to move, and to think. Those light-powered plant chemicals are used to rebuild our bodies over and over during our lives. This rebuilding is so common inside our bodies that every few years the bulk of our bodies is newly created, giving us continuity merely as a shape in which most of the tissues are repeatedly replaced.

When we are asked to define ourselves ("who are you?"), we can approach this challenge in various distinct ways. We can state that we are human and can add whether we are male or female. Moreover, we can comment on our physical features, list character traits, and include certain socio-economic factors, such as whether we are single or married, have children, are employed, and, if so, in what line of work, and at what level within an organization. Some may define themselves by their status in society, by their possessions, by their accomplishments, or by their interests and relationships. Whatever descriptions we choose, they will inevitably be rough and incomplete. They will also be influenced fundamentally by the culture and by the era into which we were born.

If, instead, we consider directly what actually constitutes us, we may think of the body and of the mind, with the two often being thought of as somewhat distinct entities. Some people may introduce the metaphysical concept of a soul or of a life force. Considering, for now, only our physical bodies, it is clear that we are made up of a hierarchy of organs, tissues, cells, and molecules. Our bodies are estimated to contain the amazing number of approximately 50 trillion human cells (using the so-called short scale for large numbers as we do throughout this book, so that means 50 million times a million cells). Within the cells that shape the human body, numerous tightly regulated processes occur to keep us alive and in a healthy state. These involve a large variety of molecules, which are composed of elemental atoms. Each cell contains an average number of atoms that is approximately as large as the number of cells in the body.

We may think of our bodies as composed of "our cells", but interestingly the majority of the cells that are contained within our overall human form are not human at all: on the inside and outside surfaces of our bodies, the bacterial cells that form what is called the human microbiome outnumber human cells by approximately 10 to 1. We are, in fact, colonized by hundreds of bacterial species. Bacterial cells are much smaller than human cells, so although they outnumber our human cells they do not considerably add to our weight. These bacteria are, however, critical factors in both health and disease because they influence complex biological processes, including the regulation of our immune system and the digestion of food. The immune system helps us ward off damaging effects of the surrounding world and digestion allows us to extract the nutrients that our bodies require from the food we eat. Thus, in order to survive we actually need this symbiosis that blurs the line between "us" and our surroundings.

Apart from the physical reality that is our body, another attribute by which we often define ourselves is our age. We rarely realize just how diverse a range of aspects we could consider in giving our age. Here, as in our thinking about what makes our physical form, considerable ambiguity arises in any attempt to formulate a straightforward number. Generally speaking, and as legally defined, our age is the time elapsed since birth. Yet we often allow for other evaluations. For example, there is the age of how we feel or of the degree of maturity with which we behave. Both are heavily influenced by the culture we live in. For example, in some places we may find many a grandmother well into her 70s who thinks nothing of going for a challenging hike each day, who dresses contemporarily, and who actively pursues a variety of interests. In contrast, we may encounter women of the same age in other cultural settings who have very sedentary lifestyles and who consider themselves as having all but lived out their lives. Not envisioning a compelling future, their behavior and presentation fully reflect that perception. The flipside of this cultural difference is that old age is frequently resisted and rejected, especially in North American culture: age is something that is fought intensely, and weapons of questionable effectiveness are eagerly supplied by the beauty and biomedical industries. In some cultures, however, a ripe old age is bestowed with certain benefits, such as elder status and an inherent association with wisdom that demands respect. Thus, to some extent, age and its interpretation are mental and cultural concepts.

Another way to address the question of age is to consider our *functional* age, which is an index of an individual's performance, taking into account a combination of the chronologic, physiologic, mental, and emotional ages and is, as such, a useful indicator of aging or "senescence", more so than time since birth alone. However, it is only our chronologic age that we typically are expected to provide as the metric of how old we are when we are asked our age.

In reality, however, even the concept of chronologic age has an unavoidable ambiguity to it. When not applied to a living being, chronologic age is generally taken to mean the length of time that has elapsed since the object was first completed. That works just fine for a painting, a piece of furniture, or a book. It quickly becomes less obvious, however, for longer-lived objects, such as an old car with many replacement parts, a road that has been resurfaced or diverted several times over, or a centuries-old house with numerous additions and repairs.

So, how old are you? That deceptively simple question can be answered in very different ways. Nine months before humans are born, at the time of conception, the genetic complement of what that human will grow into is created when an egg cell and a spermatozoon merge to create the first cell of the new individual. Both the paternal and maternal components already existed separately before that, but their merging is essentially the first moment when the blueprint of that specific human being, in strictly genetic terms, is present in the universe.

From the moment of conception onward, it takes some two decades to grow into what we consider to be an adult human. The moment of birth is clearly a differentiating moment during that time frame, and, if we were houses, we could think of ourselves perhaps as "finished", as ready to live in, after our development in the womb. During the entire growth period to adulthood, however, more material is added to our bodies than they contained at birth, and this accumulation of material does not stop when we reach the legal age that confers the status of adult. Even if we do not gain weight in later decades, which most of us do not manage to entirely avoid, the body does not cease to accumulate and process material from the world around us.

The chemicals that we take into our bodies when we eat, drink, and breathe do not simply enter and leave, but may become part of us temporarily, to help power our muscles and our brain, to repair cells, or to build new ones as earlier generations die. The original cell out of which we grew has, in all likelihood, long died. Only copies of it, differentiated to perform one of the hundreds of distinct functions within the body, continue to exist, variously lasting from days to decades, all to be replaced themselves at some time during our lives.

When we think of ourselves as a composite of cells with only temporary existence, it is evident that the conventional approach of listing our age as the number of years elapsed since birth utterly belies the complexity of the processes in our bodies. These processes reflect a sophisticated regeneration and recycling machinery that is, in turn, tightly connected to our terrestrial environment and even to our cosmic one.

We are continually rebuilt out of materials that stay in our bodies perhaps for only some days or maybe for a few years. But it goes further than that: some of the vegetables and fruits that we consume today contain energy trapped from the light that left the Sun only eight minutes before it was absorbed by a plant, and only weeks before that plant was harvested. The majority of the atoms that are present in our bodies have existed for as long as the universe has; others were forged inside stars billions (that is, thousands of millions) of years after the Big Bang, yet still billions of years in the past. Some atoms were made less than a human lifetime ago by nuclear reactions in the upper layers of the Earth's atmosphere, called the stratosphere, where commercial air traffic cruises along. What we document in this book is that this much is certain about us: very, very little in our bodies has actually been part of it for as long as what we say when we state our age. All the body parts of any living organism on the planet, be it plant or animal, are continually subject to replacement and recycling.

At some level, we are all aware of the reality of impermanence. We so often say that we no longer are who we were when we were younger. That is true enough in the psychological sense in which we generally mean it. It is particularly true, however, for the material that makes up our bodies, ranging from the water that constitutes the biggest volume of our bodies—being recycled on a time scale of days to weeks—to the very foundation of our bones and our nerve tissue, components of which may take a few decades to be largely replaced. What survives all this replacement is only a shape, a pattern, a temporary collection of matter and energy assembled into a host of specific, recognizable attributes that persist, at least for much of a lifetime.

The temporary collection of matter and energy that is a human body is a relatively flawless copy of what it was hours, days, and years ago. Even our genetic material, the DNA that lies coiled in the chromosomes in the vast majority of our cells, disappears when cells die, and is replaced in a new generation of cells. As years go by, the pattern of what we visibly are does change, yet it is still familiar enough for people to be able to recognize themselves in pictures of when they were children, and to recognize one another many years after a previous encounter. In such meetings, at high school reunions, at weddings or funerals, or in chance encounters in the street, we acknowledge that we have grown older (often perceiving more change in the other than in ourselves), but features and habits are sufficiently long-lasting for us to recognize each other, even though there may be some hesitation when much time has passed between successive encounters. Fortunately, many of our memories survive over the years, although it is unlikely that what contains these memories is composed of the same molecules that first captured them.

What it comes down to is that we are intrinsically impermanent, transient, continually rebuilt, and forever changing. We are a pattern, like a cloud, a traffic jam, or a city: even as we exchange our building blocks continually with our surroundings, the overall pattern provides enough stability for us to have a sense of continuity, both with regard to our own body and personality, and with regard to those of others.

Our bodily existence, in a way, is also akin to a wave in the ocean. The wave is a pattern of motion that travels in space and time, but the water that makes a wave at any given moment resides within it only briefly. The wave moves through, but not with, the water. Or, if we were to travel with the wave, the water would appear to flow through the wave, with as much coming into it on one side as is leaving it on the other. In the case of living organisms such as we are, the analogy with the water moving through the wave is imperfect because chemical elements and compounds stay in our bodies for different amounts of time. Nevertheless, the fundamental nature of the comparison holds true: we are a composite of patterns that are shaped by the chemical components coming into us and which travel with us temporarily before they are discarded and left behind as new ones are collected and incorporated.

We may not normally apply to ourselves directly this concept of existing only as a pattern, but with advancing technology we have become quite used to thinking in abstract terms of patterns and their evolution as copies of earlier versions. We put pictures of ourselves on social networks that friends can view on screens far away, with no idea of what was the original and what the copy. We enjoy duplicates of music files or videos on devices in our homes or on those we travel with. We email messages which, when printed, become copies that are not identical to the originals, yet carry the same content. Such persistent patterns long preceded technology and in fact surround us in the natural world every day. Let us look at a few examples.

A cloud is a pattern in which water condenses from vapor into droplets. As air moves slowly through the cloud, new droplets form while earlier ones may be lost by evaporation at the cloud's edges or by raining out of the cloud base. Another example is a river. Water moves in a river from the headwaters to the final basin, commonly a sea or an ocean. New water enters all the time, so that when we sit on the river's banks we are able to look at the one pattern that we designate "the river", but that pattern is filled with different water as time goes by and changes its shape. If we were living at a much slower pace, we would be able see the evolution in the pattern that we call a forest, too: individual trees sprout, mature, and die, yet unless that forest is cut down or burned completely, successive generations of trees form the continuing essence of this living forest. Speeding up time even more, we would see the mountains change into grains of sand as erosion takes its toll, with other mountains emerging on the Earth as a consequence of geological forces. On the longest time scales that fit within the existence of our planet, we would see continents move about, fracture, erode, and reshape, subject to the conveyor-belt motions of the seafloors. Even on the exceedingly long time scale on which stars evolve, a cyclic pattern is seen: all stars that are somewhat heavier than our own star, the Sun, explode at the end of their existence, throwing most of their matter back into the galaxies within which they formed, and new stars and planets are recycled out of that stardust to hold the pattern that is their galaxy.

The undeniable truths of impermanence and of the inadequacy of any unique definition of age apply to our environment as much as to us.

For instance, in some places the Earth itself is created anew and appears to be younger even than we are. On volcanically active islands like Hawaii one can stand on volcanic rocks that are no older than a year. One can also stand on a sandy beach that has grown markedly since the previous season. In both instances, the overall land mass is reshaped as material is moved around: from deep within the Earth to its surface on a volcanic island and from a shallow sea floor to just above sea level in the example of a beach. Volcanic rock forms by the cooling of liquid magma that has cycled inside the Earth possibly ever since our planet formed. The rock that materialized when this magma reached the Earth's surface may only be hours, days, or years old. In the case of a beach, the sand grains imply a story with more pieces to it. Once upon a time a piece of solid Earth was eroded into smaller fragments, which may eventually have been packed into sandstone and then fragmented once more, over a long period of time. This may have occurred while drifting on the ocean floor or perhaps in distant desert dunes, before finally—but just as temporarily—coming to rest on a beach that warmly supports us when we enjoy a tropical sunset. In scenarios such as these, it is easy to recognize that "age" can represent any of a variety of time scales.

The face of the Earth has changed dramatically over time, even though we might think that much of what we see has been and will be there forever. Life on Earth formed several billion years ago, but mammals have been here for only something like 60 million years, rising as the dinosaurs became extinct. Humans as a genus have existed for only a few million years. Cleary, many very substantive changes have occurred over this period, as some things were lost forever while others formed for the first time. If we focus on mankind during the past few centuries, for example, we realize that, whereas technology has changed our lives dramatically, and whereas there are definitely more humans now on the planet than 100 years ago, mankind itself is like the pattern of the wave: people are born, grow up and grow old, and eventually die, but as they come and go they flow through the pattern of mankind, which maintains a much longer and larger identity.

In the case of the universe, we typically think "age" less than "ageless". Our eyes view the stars over a negligibly small time span from the perspective of our ancient universe. To them, the Galaxy is a vast, still, and steady cradle for our small planet. We readily observe the cycles of the Moon and we unavoidably live with the daily rising and setting of the Sun. Apart from these familiar motions, however, nothing seems to change. If we measure precisely enough, we can establish that the stars and the planets are moving through the firmament, but on the cursory inspection that we commonly afford the skies, the universe appears to us to be static. We usually do not stop to think that some of the stars that twinkle in the midnight sky were extinguished eons ago, their light having left the distant star perhaps thousands of years before that, still traveling toward us as the star itself exploded and vanished. Despite the universe's appearance as a timeless, permanent fixture, individual objects in space have different ages too. We can trace back the universe as a whole to moments after the Big Bang, but most of the stars, planets, and other heavenly bodies that make up the uncountable galaxies have not existed since the beginning of time. Instead, early generations have "died" while new ones have been formed.

Realizing how fluid we are and how impermanent everything around us truly is, we should think differently about the materials that we take into our bodies to quench our thirst and feed our hunger: this material does not simply flow through our gut, but is assimilated into the very structure of our bodies until, after some time, it leaves it again in some other form. Our bodies are very complex chemical machineries, as are those of all living things on this planet, but the mixture of the elements used in our chemistry simply reflects what is readily available around us in a chemically useful form and quantity. From this, it follows quite logically that the most common elements in the planetary system are the same as the most common elements in our bodies, albeit with some notable exceptions that we can easily understand.

Not only the elements in our bodies, but all processes on the Earth are directly connected to those in our solar system, to our Galaxy, and to the universe beyond. From that perspective, it becomes understandable not merely that life on Earth reflects the elemental makeup of the solar system, but that the solar system in turn reflects the elemental makeup of the Galaxy around it. Once mankind learned the true nature of stars and realized that they are vast nuclear furnaces that shape and destroy the planets around them, and when a better understanding emerged of the central role of stars in establishing the contents of the universe, it became clear that we are, indeed, stardust, in a very literal sense. Every object in the wider universe, everything around us, and everything we are, originated from stardust. Thus, we are not merely connected to the universe in some distant sense: stardust from the universe is actually flowing through us on a daily basis, and it rebuilds the stars and planets throughout the universe as much as it does our bodies, over and over again. In our everyday lives, we tend to ignore the universe beyond the Earth's atmosphere and take it for granted that the Sun steadily shines its warming light onto the planet. We do not generally ponder the many links between us and the stars, except perhaps for the links to the nearest star that we call the Sun. These links range from the Big Bang, in which the universe was formed, to the particle radiation from the Galaxy that slams into the high terrestrial stratosphere right now.

With the exception of hydrogen, which formed when the universe itself was created, almost all of the atoms in our bodies have been forged either in the deep interior of stars, or within the explosion of these stars at the ends of their existence.

One key connection between ourselves and the universe and, indeed, an essential ingredient of life, has yet to be discussed: energy. It is energy that maintains the surface of the Earth well above the cold of the ambient universe, which is a mere three degrees above absolute zero and thus hundreds of degrees below freezing. In units that we encounter more frequently, this translates into about minus 455 degrees Fahrenheit or minus 270 degrees Celsius. Without an external energy supply, life on Earth as we know it would be simply impossible. The external energy raises the Earth's temperature so that it can support plants, which, in turn, feed animals, including us.

The bulk of the energy that is available to life on our planet comes from the Sun. Only a very small fraction of the Earth's overall energy budget is liberated from the radioactive decay of stardust in the Earth's interior. This afterglow of stellar deaths deep inside the Earth manifests itself to us on the surface as geothermal or volcanic energy. This energy is primarily liberated from the decay of uranium, thorium, and potassium, which were formed as stars exploded at the ends of their lives.

Even the Sun's radiant energy is a form of stardust. The energy of the Sun's light is ultimately generated in the deep solar interior by violent nuclear collisions. Mass and energy are equivalent and exchangeable: the solar light that hits the Earth loads the equivalent of about 140,000 tons of mass onto our planet every year. Much of that load is there only briefly, because a lot of the sunlight shining down on the Earth is reflected back into space by the clouds, oceans, and land masses, but part of it is stored in plants for days or weeks and then can be processed in a great diversity of ways. It may be used to build the compounds that constitute our bodies and to power the network of metabolic reactions that