
We Are Stardust
Stellar Evolution and Our Cosmic Connection
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Robert Fleck
Emeritus Professor of Physics and Astronomy
Department of Physical Sciences
Embry-Riddle Aeronautical University
Daytona Beach, FL, USA

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We are stardust
Billion-year-old carbon…

—Singer-songwriter Joni Mitchell, "Woodstock" (1969)

Stars have a life cycle much like animals. They get born, they grow, they go through a definite internal development, and finally they die, to give back the material of which they are made, so that new stars may live.

—Hans Bethe concluding his 1967 physics Nobel acceptance speech

… we have found it possible to explain, in a general way, the abundances of practically all the isotopes of the elements from hydrogen through uranium by synthesis in stars and supernovae.

—F. Hoyle, William A. Fowler, G. R. Burbidge, and E. M. Burbidge, "Origin of the Elements in Stars," *Science* **124** (1956, p. 611)

We are made of stardust. Every atom of every element in your body except for hydrogen [a product of the Big Bang 13.8 billion years ago] *has been manufactured inside stars, scattered across the Universe in great stellar explosions, and recycled to become part of you.*

—John Gribbon, *Stardust* (2000, p. 1)

All of the rocky and metallic material we stand on, the iron in our blood, the calcium in our teeth, the carbon in our genes were produced billions of years ago in the interior of a red-giant star. We are made of star-stuff.

—Carl Sagan, *The Cosmic Connection* (1973, pp. 189–190)

… we are the local embodiment of a Cosmos grown to self-awareness. We have begun to contemplate our origins: starstuff pondering the stars, organized assemblages of ten billion billion billion atoms; tracing the long journey by which, here at least, consciousness arose… Our obligation to survive is owed not just to ourselves but also to that Cosmos, ancient and vast, from which we sprang.

—Carl Sagan, *Cosmos* (1980, p. 345)

You are a child of the Universe…

—Max Ehrmann, *Desiderata* (1927)

For you are dust and to dust you shall return.

—Genesis 3:19

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It is a pleasure to acknowledge, once again, the encouragement and support of Angela Lahee, physics executive editor for Springer Publishing. And once again, I thank a lifetime of students for working with me to understand the life cycle of stars, the very essence of our cosmic connection. It has been a pleasure and a privilege to have spent a lifetime in the classroom with all of them. I thank Joni Mitchell for long ago opening my eyes—and ears—to our *real* cosmic connection through her beautiful music, true "music of the spheres." There will never be another like her.

I dedicate this book to all the children of the stars—all of us star-stuff star folk—riding together on this rock we call Earth around the Sun, our star in the Cosmos, with the hope that, appreciating our common cosmic connection, we will all make the ride safer and better for everyone, for the rock itself and all the life it supports, and for all who will follow on this cosmic journey.

... still on the Beach in Daytona — Robert Fleck
USA
June 2024

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About the Author

Robert Fleck is Emeritus Professor of Physics and Astronomy in the Department of Physical Sciences at Embry-Riddle Aeronautical University in Daytona Beach, Florida, where for four decades he developed and taught a large number and a wide variety of undergraduate and graduate courses in physics, astronomy, general science, and history of science. For inspiring his students with his passion and enthusiasm for teaching and lifelong learning, he received the University Outstanding Teaching Award in 2000 and 2015, as well as over a dozen faculty appreciation awards from graduating senior classes. Professor Fleck is a NASA and National Science Foundation supported star and planet formation theorist; he has published in a wide variety of disciplines, including physics and astronomy and the history of science, and he has been a Visiting Scientist at the National Radio Astronomy Observatory and a Perren Visiting Fellow at the University of London. He also pioneered Embry-Riddle's study abroad program, teaching classes in England, France, Italy, and Greece, and he has completed two book-length manuscripts titled *The Evolution of Scientific Thought: A Cultural History of Western Science from the Paleolithic to the Present* and *Art History as Science History: Picturing the History of Science from the Paleolithic to the Present*. His recently published book is *Entropy and the Second Law of Thermodynamics …or Why Things Tend to Go Wrong and Seem to Get Worse*. When not reading or writing, he enjoys swimming, surfing, cycling, and traveling.

1

Introduction

Summary In the days before books and television, before computers and cell phones, before Facebook and Instagram, our ancient ancestors watched and wondered about their place in the Universe and composed stories—myths—to organize their experiences, many of which expound some aspect of cosmic order. Modern science has shown that, in a very real and profound sense, we are intimately connected to the Cosmos: we—and all we see around us—are a natural product of the workings and wonders of the Universe. This introductory chapter summarizes this book's purpose to help the reader understand and appreciate this cosmic connection, that we are, in fact, tied directly to distant events spread across the Universe in space and time reaching back to the beginning, back to the Big Bang, and continuing through the birth and death of successive generations of stars. We are stardust—in a very real sense, children of the stars—star folk made from chemical elements ("star stuff") created by nuclear reactions in stellar furnaces and distributed throughout the Galaxy during the various stages of stellar evolution. Whether or not the stars above us govern our conditions (through astrological influences, as suggested, for example, in William Shakespeare's *King Lear*), they have certainly helped *create* our conditions—and, significantly, since these processes occur throughout the Galaxy, the conditions for life throughout the Universe. It is hoped that the reader will leave, awed by the power and beauty of this cosmic perspective, with a better understanding and appreciation of our true cosmic connection.

R. Fleck, *We Are Stardust*, https://doi.org/10.1007/978-3-031-67275-0_1

We are stardust
Billion-year-old carbon . . . .
—Singer-songwriter Joni Mitchell, "Woodstock" (1969)

… if you ask about the origin of the [chemical] *elements … the answer is that hydrogen and helium are left from an early, hot, dense phase in the life of the Universe (called the Big Bang); all the rest were made by the stars.*
—astronomer Virginia Trimble, "The Origin and Evolution of the Chemical Elements" [1, p. 63]

In *Cosmos*, a hugely popular story of the Universe and our place in it,[1] the late astronomer Carl Sagan finds "something curious about the national flags of the planet Earth": almost half display astronomical symbols such as stars (one for many countries including Russia and Israel, five for China, fifty for the United States with stars featured on nearly half the state flags as well), the Sun (e.g., Japan and Argentina), the crescent Moon (Turkey and many of the Islamic states), the celestial sphere (Brazil), various constellations (e.g., Australia and New Zealand), as well as a variety of cosmological symbols (e.g., India and South Korea). "The phenomenon," Sagan points out [2, p. 50],

> is transcultural, nonsectarian, worldwide. It is also not restricted to our time: Sumerian cylinder seals from the third millennium BC and Taoist flags in prerevolutionary China displayed constellations. Nations, I do not doubt, wish to embrace something of the power and credibility of the heavens. *We seek a connection with the Cosmos* [emphasis added]. We want to count in the grand scale of things. And it turns out we *are* connected—not in the personal, small-scale unimaginative fashion that the astrologers pretend, but in the deepest ways, involving the origin of matter….

Indeed, we have always looked to the heavens for inspiration and answers; there is something uplifting and comforting about looking up to the sky at

[1] Although some parts are, not surprisingly, a bit outdated (thus does science advance), Carl Sagan's *Cosmos*, the book that accompanied the 1980 PBS documentary series of the same title, is still well worth a read. I remember reading it when it first appeared in the early years of my career shortly after leaving university with a Ph.D. in astronomy. Of course, I found the science fascinating and, Ph.D. notwithstanding, I learned a lot of astronomy. But even more than that, what really impressed me was the breadth of Sagan's knowledge reaching far outside the confines of astronomy, and his almost superhuman ability to share that knowledge and enthusiasm. His book opened my eyes to the world outside astronomy, inspiring me to learn all that I can about all that I can. When I think of genius, Sagan still sits atop all others in ability to communicate science effectively and enthusiastically, a rare and much needed talent especially today (see, e.g., Brandon Brown's *Sharing Our Science: How to Write and Speak STEM*, MIT Press, 2023; others I place in the genius category include The Beatles for music, Robin Williams for humor, and the 1972 Miami Dolphins for football). Give *Cosmos* a read. You won't be disappointed.

night [3–5].[2] After providing for the food and shelter necessary for survival—the essentials biologists call the "four Fs" of life: feeding, fighting, fleeing, and mating—our ancient ancestors, in the days before books and television, before computers and cell phones, before Facebook and Instagram, watched and wondered about their place in the Universe. Despite the proliferation of modern distractions, we still wonder, and we still ask ourselves fundamental questions regarding our origin, purpose, and destiny (Fig. 1.1).[3] Different cultures ask different questions seeking different kinds of knowledge and often arrive at answers, different kinds of "truths." As we became better at figuring things out, our answers to these questions evolved through increasing stages of sophistication, progressing from primitive mythic narrative to recognizably mature scientific responses.[4]

As Sagan reminded us [2, pp. xii, 318],

> … science has found not only that the universe has a reeling and ecstatic grandeur, not only that it is accessible to human understanding, but also that we are, in a very real and profound sense, a part of the Cosmos, born from it, our fate deeply connected with it….
>
> Something in us recognizes the Cosmos as home. We are made of stellar ash. Our origin and evolution have been tied to distant events….
>
> As the ancient mythmakers knew, we are the children equally of the sky and the Earth.…

[2] Uplifting and more. "It is one of the ironies of history," historian of science John North concludes in his historical survey of astronomy and cosmology [6, p. 623], "that the study of such a vast and impersonal subject matter [i.e., astronomy] should from beginning to end have been so intimately bound up with principles of human nature." Most early societies were organized around the sky, often associating their gods with celestial bodies, and most of us today continue to be fascinated with the study of astronomy.

[3] Consider the "rationale" for a recently advertised symposium sponsored by the International Astronomical Union titled "(Toward) Discovery of Life Beyond Earth and its Impact":

> From our origins, humans have been inspired by pinpoints of light in the night sky. They cause us to wonder about our existence. Who are we? What are we doing here? Where did we come from? And, where are we going?. . . Despite impressive investment and activity in space exploration over the years, the question remains unanswered.

Gauguin's questions (see Fig. 1.1) still strike at the heart of modern science.

[4] See, for example, J. Norman Lockyer's 1894 *The Dawn of Astronomy* [7], a pioneering study of the interplay of archaeology and astronomy in the ancient world. Lockyer identified three advancing stages in the historical development of astronomy: the mythical, the practical, and the intellectual. Although Lockyer confined his attention to astronomy in particular, one could easily assign these developmental stages to science in general. The developmental stages in our understanding of our connection to the Cosmos are examined in subsequent chapters.

Fig. 1.1 French post-Impressionist artist Paul Gauguin's monumental (measuring nearly five feet by just over 12 feet in size) 1897 *D'où Venons Nous/Que Sommes Nous/Où Allons Nous* (*Where do we come from? What are we? Where are we going?*), now in the Boston Museum of Fine Arts. The title in French verse appears in the upper-left-hand corner of the painting which was made during the artist's Polynesian period. Ever since we became conscious of ourselves and the world around us, we have asked "ultimate" questions such as these regarding our origin, purpose, and destiny. We know from a surviving manuscript in which he extolled his philosophical musings about human destiny, that Gauguin considered the role that new scientific knowledge might play in resolving such questions. In any case, it is significant that when Gauguin posed them, science was not in a position to provide answers; one would have had to consult philosophers or theologians. Today, however, more than a century later, science has come a long way in answering these most profound of questions that still lie at the heart of philosophy and modern science—even if, to the dismay of author John Gribbin, "hardly anybody outside a small circle of scientific specialists seems to have noticed" that "[w]e have answered the biggest question of them all—where do we come from?" [8, p. 177], Gauguin's leading question here. Even more profoundly, the late English theoretical physicist and cosmologist Stephen Hawking wanted to know *Why* are we? (*Wikimedia Commons, public domain*)

As a star and planet formation theorist, I have for a long time wanted to write this book about our *real* cosmic connection, our connection with the stars, not the presumed numinous connection suggested by the ancient pseudoscience of astrology, but rather a most intimate connection now recognized by science: the fact that, as Joni Mitchell sings in her song "Woodstock," "we are stardust," all of us—bones, blood, and brains—children of the stars, star folk all made from the same stuff—star stuff—all brought into existence with the birth of the Universe and the evolution—the change in the structure and composition from birth to death—of stars. The oxygen in the air we breathe and in the water that makes up most of our body mass, the carbon so essential to all organic material, the nitrogen in our amino and nucleic acids that are the building blocks of our proteins and genetic material, the calcium in our bones and teeth, the iron in our blood—*all of us—and all that we see around us are a natural product of the workings and wonders of the Universe* (Fig. 1.2).

Fig. 1.2 *Arizona*, painted in 1979 by the American artist Ray Swanson (1937–2004). While it may not have been the primary intent of the artist, Swanson's painting (and several others such as *Monument Valley Lady* and *Eskimo Lady and Her Land*) are vivid illustrations of our cosmic connection, that we and everything around us share a common origin deep in the history of the Universe, a view that resonates with that of Indigenous Peoples, who believe that *all* things are connected, that we are people equally of Earth and Sky. Note the remarkable similarities in color and form of the age-worn Navaho woman and the eroded ancient rock formations of Arizona's Grand Canyon. (*Courtesy of the Ray Swanson family estate. Used with permission*)

Astrophysicist John Gribbin makes it very clear in the final sentence of his book: "We are made of stardust because we are a natural consequence of the existence of stars," adding, as a result, addressing what is perhaps the only other ultimate cosmic question—the question of life elsewhere in the Universe—that "from this perspective it is impossible to believe that we are alone in the Universe" [8, p. 187; recall Note 3].

Our story begins where the Universe itself began: with the Big Bang some 13.8 billion years ago when, during the first three minutes in the history of the Universe (to borrow from the title of Physics Nobel laureate Steven Weinberg's account of the origin of the Universe [9]), all of the hydrogen and most of the helium—by far the most abundant elements in the Universe which is roughly three-quarters hydrogen and one-quarter helium by mass—formed from a cooling plasma of protons, neutrons, and electrons.[5] We then

[5] All the stuff ("stof" is Danish for "matter") that we see all around us (including us) all the way out to the farthest reaches of the Universe—what we call *baryonic matter* because it consists primarily of the two most common baryons, positively charged *protons* and electrically neutral *neutrons*, the basic building blocks of ordinary matter—amounts to just under 5% of the total mass-energy of the Universe. (Recall that in his theory of relativity, Albert Einstein demonstrated the equivalence of mass (m) and energy (E) which are related by arguably the most famous equation in science, $E = mc^2$, c denoting the speed of light—at 186,000 miles per second a *very* big number—nearly as fast as the speed of *life*!—so even a little mass contains a lot of energy.) The word "baryon" comes

trace the life cycle of the stars from birth to death—*stellar evolution*—highlighting the synthesis in self-gravitating nuclear fusion reactors called stars, of the heavier chemical elements so essential to life, along the way touching on many of the hot topics in astrophysics today including exoplanets, supernovae, pulsars, black holes, white dwarfs, and life in the Universe, all with a minimum of mathematics (developed mostly in Notes that, in any case, can be skipped over). "You are a child of the universe" the American author Max Ehrmann reminds readers of his prose poem, *Desiderata*, written a century ago, "stardust, billion-year-old carbon," Joni Mitchell sings. Humans—and all life on Earth sharing a common carbon chemistry—are, as the film *Star Trek: The Motion Picture* reminded us, "carbon-based units."[6] Indeed, *life as we know it is an inevitable consequence of the life cycle of the stars*.

from the Greek "barus" meaning "heavy": the other component of ordinary matter, the electron, carrying a negative electric charge equal in magnitude to the positive charge of the proton, is some two-thousand times lighter than the proton and neutron which have nearly the same mass—nearly the same, but, as we'll see, importantly not exactly the same: the neutron is slightly more massive than the proton. (The *electron* is the most common type of *lepton* [Greek, "small"]; the nearly massive *neutrino* is also a lepton and is the most abundant elementary particle with mass in the Universe, perhaps more abundant than the *photon*, the particle of light—even if it has no electric charge and so little mass that it is so difficult to detect.) And so, for us, there are only three primary constituents of ordinary matter—one less than the four of ancient Greece (earth, water, air, and fire).

Amazingly, most of the stuff in the Universe is dark (invisible to the eye), and although we have no idea what it is (if you, the reader, have any ideas, please share them with me: I'll win the Nobel Prize and I'll buy you a beer), we do know that it's about three quarters *dark energy*, mysterious stuff that, among other things, drives the expansion of the Universe, and about one quarter *dark matter*, stuff we know is out there because of the way it interacts gravitationally with the ordinary matter we can see, each one merely a label for our ignorance. Astronomer John Barrow refers to this as "the final Copernican twist to our status in the material universe. Not only are we not at the center of the universe; we are not even made out of the predominant form of matter in the universe" [10, p. 74]. (Interestingly, but nonetheless coincidentally, the proportion of dark energy to dark matter mirrors that of hydrogen to helium, the bulk of ordinary matter in the Universe.) Dark matter was once called "missing mass" because, although it reveals itself dynamically, we can't see it so it is, in that sense, missing. Rather like a nighttime map of Earth from space doesn't faithfully represent population density, mirroring instead the distribution of wealth, a map of the light distribution in the Universe is not a good guide of the distribution of matter. I have to admit that I'm totally in the dark over all of this dark stuff (although I often wonder if dark matter might be lost airline luggage), but a lot of clever people are looking into the matter, so to speak—and actively looking for the stuff. Not an easy task, as you can imagine. Stay tuned.

[6] Carbon is the fourth most abundant element in the Universe after hydrogen, helium, and oxygen. It's the basis of organic chemistry, the chemistry of life. Carbon's ability to form stable bonds with many elements, including itself, allows it to form a large variety of very large and complex molecules required for life processes. All living organisms on Earth contain a total of 550 billion tons of carbon, second only to oxygen, out of about 3.6 trillion tons of biomass [11].

Here is Carl Sagan's succinct one-paragraph account in biblical cadence of the Universe's first 10 billion years [2, pp. 337–338; emphasis added]:

> For unknown ages after the explosive outpouring of matter and energy of the Big Bang, the Cosmos was without form. There were no galaxies, no planets, no life. Deep, impenetrable darkness was everywhere, hydrogen atoms in the void. Here and there denser accumulations of gas were imperceptibly growing, globes of matter were condensing—hydrogen raindrops more massive than suns. Within these globes of gas was first kindled the nuclear fire latent in matter. A first generation of stars was born, flooding the Cosmos with light. There were in those times not yet any planets to receive the light, no living creatures to admire the radiance of the heavens. *Deep in the stellar furnaces the alchemy of nuclear fusion created heavy elements, the ashes of hydrogen burning, the atomic building materials of future planets and lifeforms*. Massive stars soon exhausted their stores of nuclear fuel. Rocked by colossal explosions, they returned most of their substance back into the thin gas from which they had once condensed. Here in the dark lush clouds between the stars, new raindrops made of many elements were forming, later generations of stars being born. Nearby, smaller raindrops grew, bodies far too little to ignite the nuclear fire, droplets in the interstellar mist on their way to form the planets. Among them was a small world of stone and iron, the early Earth.

Eventually, some 13.8 billion years after the Big Bang and 4.5 billion years after Earth formed, the "ash of stellar alchemy" emerged into consciousness. Humankind arrived. This is the story developed here, our story, the story of our cosmic connection.[7] It has, as Sagan admits, "the sound of epic myth." But, Sagan continues, "it is simply a description of cosmic evolution as revealed by the science of our time." I hope that you, the reader, will leave, awed by the power and beauty of this cosmic perspective, with a better understanding and appreciation of our true cosmic connection.

To me, as an astrophysicist—as a human being—*our understanding that the stuff we are made of traces its origin to nuclear processes accompanying the Big Bang, and thereafter to billions of years of the birth and death of generation*

[7] John Gribbin's *Stardust* has been the only accessible detailed account of our cosmic connection, although, like Sagan's *Cosmos*, it is now somewhat outdated (for example, very recent evidence suggests that many of the heaviest elements, like the silver and gold in your jewelry and the uranium that fuels our nuclear reactors, are produced explosively during neutron star mergers). His differs from mine in that, like Sagan, I have woven historical antecedents and cultural consequences into my story; Gribbin focuses entirely on the science. Surprisingly, despite its profound significance—cosmically and otherwise—this fascinating story of our connection to the stars has largely gone unnoticed: as Gribbin complains [8, p. 177], "hardly anybody outside a small circle of scientific specialists seems to have noticed." Such a beautiful story certainly deserves more attention. *You Are Stardust* by Elin Kelsey (Owlkids Books, Toronto, 2012) shares the same storyline with children, little ones who are naturally curious about everything (would that we all could remain children).

after generation of stars, is one of the most profound and inspiring discoveries ever made, certainly *the* most fundamental and fascinating finding about ourselves and our connection to the Cosmos. This was the most important message I hoped my students would take away from their study of astronomy. I'm not alone in my rhapsodic feelings here: introducing *Carl Sagan's Cosmic Connection*: *An Extraterrestrial Perspective* with her essay "Carl Sagan: A New Sense of the Sacred," Ann Druyan, Sagan's one-time wife and award-winning producer and director who co-wrote the 1980 PBS documentary series *Cosmos*, admits to a

> soaring spiritual high that is science's overarching revelation—our oneness with the cosmos…. We are starstuff. You, me and everybody. Not the failed clay of a disappointed Creator, but, literally, down to every atom in our bones, the ash of stars [12, p. xxvi].

Like Carl Sagan and many others, I like to think that the world will be a better place if more of us realize this place wasn't put here for us, that we are not the "crown of creation" (to borrow from a Jefferson Airplane 1968 album and song title) but rather part of a larger scheme in an indifferent Cosmos, nothing more—or less—as Sagan reminds us, than "the latest manufactures of the galactic hydrogen industry" [2, pp. 338–339]. Sagan believed that "The deflation of some of our more common conceits [our "naïve self-love"] is one of the practical applications of astronomy" [12, p. xxx]. And I hope that you the reader will, like the famous Nobel Prize-winning physicist Richard Feynman, experience "the pleasure of finding things out" (to borrow from the title of his book [13]; Fig. 1.3), and will appreciate our cosmic connection as an antidote to the feeling of insignificance when contemplating the immensity of the Universe. Besides, as Steven Weinberg confesses in the final sentence of his blow-by-blow account of the Universe's *First Three Minutes* [9, p. 155], "The effort to understand the Universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy."

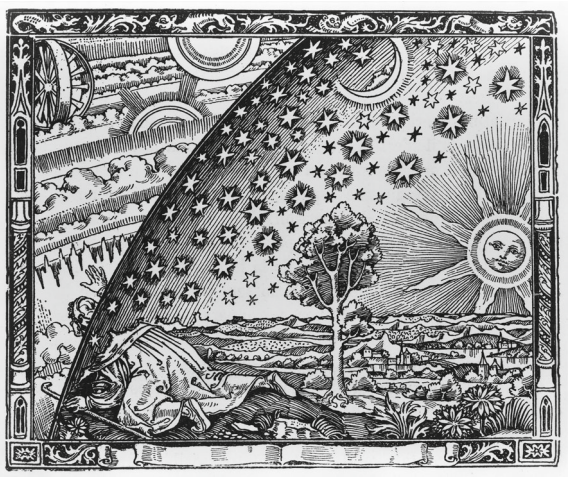

Fig. 1.3 Following Feynman in experiencing "the pleasure of finding things out" in a quest for knowledge—in this case here, wondering about the workings of the Universe and our place in it—a cosmically curious observer peaks through Shakespeare's star-studded "brave o'er hanging firmament" to explore the mysterious Empyrean beyond in this illustration taken from the French astronomer Camille Flammarion's *L'Atmosphère*: *Météorologie Populaire* (*The Atmosphere: Popular Meteorology*) published in Paris in 1888, a time when we could only imagine our cosmic connection. Today we know we are connected to the Cosmos in the most materially intimate way. (*Wikimedia Commons, public domain*)

References

1 V. Trimble, "The Origin and Evolution of the Chemical Elements," in *Origin and Evolution of the Universe: From Big Bang to Exobiology*, 2nd edn., ed. by M. A. Malkan, B. Zuckerman (World Scientific, Singapore, 2020), pp. 63–97
2 C. Sagan, *Cosmos* (Random House, New York, 1980)
3 E.C. Krupp, *Beyond the Blue Horizon: Myths and Legends of the Sun, Moon, Stars, and Planets* (HarperCollins, New York, 1991)
4 J. Marchant, *The Human Cosmos: Civilization and the Stars* (Dutton, New York, 2020)
5 R. Trotta, *Starborn: How the Stars Made Us (and Who We Would Be Without Them)* (Basic Books, New York, 2023)
6 J. North, *The Norton History of Astronomy and Cosmology* (W. W. Norton and Company, New York, 1994)
7 J. N. Lockyer, *The Dawn of Astronomy.* (Dover Publications, Mineola, NY, 2006; orig. publ. Cassell and Company Ltd., London, Paris & Melbourne, 1894)
8 J. Gribbin, *Stardust* (The Penguin Group, Chatham, UK, 2000)