CONTENTS

	Introduction	1
1	The Discovery, Origin, and Dispersal of Carbon	9
2	The Chemistry of Carbon: Why Is It So Special?	33
3	Carbon on Earth and in the Solar System	51
4	Carbon and Life on Earth and Elsewhere	69
5	Carbon in the Milky Way	106
6	What Is Carbon Good For?	127
7	Diamonds	157
8	The Atmosphere, Climate, and Habitability	181
9	Carbon Out There	202
	Epilogue: Carbon: From the Beginning to Infinity	212

Notes 221
References 227
Index 233

Introduction

In a Universe of wonders, carbon is truly a wondrous element. Carbon can be hard or soft, sooty black or clearer than crystal. It was forged in the fiery interiors of stars; in its clear diamond form, it feels cold in your hand; and out of your hand, it is the very best conductor of heat. Burning forms of carbon produced heat that kept humans warm for millennia and energy that powered the Industrial Revolution. We eat tons of it in our lifetime, and the unique chemical prowess of this Swiss army knife of chemical elements forms the virtual backbone of life as we know it. We are made of it, as Joni Mitchell wrote in her song "Woodstock," "We are stardust . . . billion year old carbon."

This book is dedicated to just one of the naturally occurring chemical elements. Carbon is considered the sixth element because it has six protons in its nucleus and six electrons to balance the protons' positive charge. Considering its abundance in the Sun, carbon ranks as the fourth most abundant element after hydrogen, helium, and oxygen. Oddly enough, despite its high abundance in stars, carbon is relatively rare inside our planet. We see lots of it near the Earth's surface, where we live, but averaged over the whole planet, it is actually a rare element. We live in a carbon-rich environment on the surface of a carbon-poor planet. We will explain how this happened and why we are different from many outer solar system bodies in chapter 3.

In this book we also discuss how carbon was discovered and how understanding this important element was a major advancement of our scientific understanding of nature. We will see how it is made in stars, how carbon atoms ended up on Earth, and why it can form so many compounds that are key to our existence. We will explore some of the impacts that the sixth element has had on human history, many of its remarkable uses, and its role in the past and future of our planet.

Like other elements heavier than hydrogen, carbon is just a tiny core of comparatively massive protons and neutrons that is surrounded by electrons. Carbon, however, is unlike all the other elements in its ability to bond with other atoms to make materials with an extraordinary range of chemical and physical properties. When other atoms are involved, a nearly unlimited number of compounds can be made, including some very complex ones that enabled the formation of life and then evolved over geologic time to produce the living organisms that we know of.

Carbon may be just one of nearly a hundred naturally occurring elements, but it stands out from all the others. As a pure element, it can exist in such diverse solid forms as soot, graphite, diamond, buckyballs, nanotubes, and sheets of carbon lattice only a single atom thick. When bonded to other elements, it can form a nearly infinite number of compounds. These compounds are so important that they are granted their own class of "organic chemistry."

There are several known natural forms of pure elemental carbon, and at least one unnatural one. The simplest pure carbon form is just a single atom. This is not found on Earth, because carbon atoms stick to everything and form molecules. Only in the isolation of interstellar space are single-carbon atoms found. Next are carbon chains, carbon atoms in line, which also exist naturally only in interstellar space.

When carbon atoms bond to each other, they can form sheets named graphene. When graphene sheets stack together, which is easy, we have graphite, the stuff that allows pencils to make black lines. Carbon sheets can curl up to form tiny hollow nanotubes. The next in complexity are the fullerenes, named after Buckminster Fuller. The most abundant fullerene in nature is the semispherical molecule C_{60} that resembles a soccer ball. Carbon famously also forms crystals of the superlative mineral diamond, to which we dedicate one chapter. Rings of pure carbon are also possible: cyclocarbon, with eighteen carbon atoms, is the only one that has been made. It was predicted in theory but not produced until 2019. So, even with the incredible diversity of carbon that we do know about, there is always more to discover.

As astronomers, we have inevitably put a broad cosmic focus on the many aspects of carbon. As scientists, we have placed strong emphasis on the fundamental science issues involved with this special element. And because of carbon's incredible role in both the history of humans and science, we have also chosen to view carbon through a lens of history. The broad range of carbon's history involves its origin, how it served as a fundamental gateway to the formation of nearly all of the other chemical elements, how it evolved in space, how it got to Earth, and how it was used to make life and drive the evolution of our planet. Early human dealings with carbon led to making fire and cave paintings, and then evolved into the foundations of science and our first understandings of atoms and what matter actually is. History does not end now, and the findings of both physics and astronomy clearly show the basic roles that carbon will play even trillions of years into the future, as it cycles between vastly different environments and is ultimately destroyed in the difficult-to-fathom deep time of the distant future.

One of the most challenging scientific endeavors of our time is predicting and understanding the future effects of the buildup of carbon dioxide and its effects on crops, polar ice, sea level, weather, and the global economy. Carbon is unique among elements in that it has such serious implications for our planet, and for our lives. Like it or not, the energy that drives the modern world, as it has since the first cavemen, is still largely derived from the chemical reaction of burning carbon compounds to produce carbon dioxide. It is the only element in the periodic table that has its own tax. Beginning with Finland in 1990, many countries now have some form of carbon tax as a way to stimulate migration to other forms of energy generation and reduce production of the greenhouse gas carbon dioxide. We will discuss some of these issues in chapter 8.

In our first biology class, we learn that life is based on carbon and that this element is unique in its ability to make strong bonds with itself and many other important elements. Yet the many roles of carbon and its unique properties and chemistry remain often underappreciated. Our main purpose in writing this book is to display as many of the glories of the sixth element as we can, from the earliest known writings and drawings to the latest nanotechnologies; from its birth in stars to its role in the formation of Earth to its many lives in the tools humans have created from it to sustain life and also to beautify and enhance it; to build; to invent; and to pass literature, art, music, laws, math, and other forms of accumulated knowledge to future generations.

In chapter 6, we focus on the amazing materials, tools, and technologies the sixth element has spawned, and some of the ways they have shaped history and our everyday lives. To take just one example, consider the important role carbon has played in making recorded history possible. As far back as twenty thousand years ago, charcoal was used in making the famous Paleolithic cave paintings in the Dordogne region of southwestern France, and for most people who are now alive, much of what they have learned was learned from reading letters printed in black carbon. Until recent times, carbon was used to create nearly all written or printed words. The Magna Carta, the Declaration of Independence, and, of course, all literature before computer-based word processing was written with microscopic carbon particles preserved in ink, or with pencil "lead," which is a mix of carbon and clay.

Another often unappreciated function of carbon in our lives is its fundamental role in providing us with color. Except for the ocean and sky, most of the color that enriches our daily lives involves carbon compounds, even if they are just a binder holding inorganic pigments together. Some color pigments are derived from coal tar or other petrochemicals. Our quite colorful, carbon-coated world provides a stunning contrast to Mars, the Moon, and Venus, our comparatively drab neighbors in space. Except for invisible carbon dioxide, these bodies do not contain appreciable amounts of carbon compounds. They are not covered with plants or paints, so they are mind-numbingly monochromatic, either gray or reddish.

The sixth element provides us with an astonishing number of capabilities that might be commonly overlooked. Steel, the backbone of most buildings, bridges, vehicles, and modern warfare, is not just iron; it is iron strengthened by the addition of small amounts of carbon that dramatically improve its properties. Cars, trucks, and buses ride on a miracle material, "rubber" tires, made of a mix of microscopic carbon particles held in a matrix of carbon polymers. The roads that these vehicles travel on are paved with either asphalt or concrete. Asphalt is a mix of petroleum and rock. Concrete is made with rocks, lime, and clay. Lime, a key ingredient, is made from roasted limestone. Limestone is by far the dominant form of carbon in our planet's outer layers. Just the production of concrete for roads and construction is responsible for an astounding 5 percent of the human-produced carbon dioxide that is being put into the atmosphere.

All of the foods that people and animals eat, as well as most of their packaging materials, are composed of carbon compounds. The diamonds you wear and those used to saw slabs of granite countertop out of cliffs are forms of pure carbon. The air you breathe is dominated by nitrogen and oxygen, but carbon dioxide, present in minor concentrations (0.04 percent), plays major roles in governing the long-term habitability of our planet and, of course, is the source of the carbon that allows giant trees and all plants to grow with energy provided by sunlight. This gas, although enjoyed in champagne and fizzy drinks, is commonly derided because of its role in global warming. It is an irony of nature that we can't live without this "toxic gas," because it is the "food of life" on our planet.

We will talk about plastics, carbon compounds that have revolutionized our society. There are natural plastics, such as amber, but humans have produced nearly 10 billion tons of synthetic plastics since the Second World War, usually from petroleum, of which carbon is the main component. Plastics have become ubiquitous both as litter and as products that we can't live without. Though plastics are often associated with waste and pollution of the Earth and oceans, they also enrich our lives in remarkable ways. The uses of plastic are seemingly endless, and some of our highest-tech materials are plastics. For example, a composite of epoxy and graphite fibers is used to make products that include spacecraft, tennis rackets, airplanes, skateboards, expensive cars, and warheads for ICBMs. The highest-quality displays for televisions and phones are made of organic light-emitting diodes (OLEDs). The use of the word "organic" in the OLED acronym does not mean that it was grown on a pesticide-free OLED farm, but rather that it is made of carbon-based molecules containing carbon-hydrogen and perhaps carbon-carbon bonds. This "misunderstanding" is an example of the common misuse or at least an alternative use of a scientific term. By scientific definition, CO, CO_2, and cyanide are not organic molecules, though almost every food item in a grocery store (including conventionally grown vegetables) is made of organic chemicals.

It is hard to imagine living in the modern world without plastics. A simple example is the elegance of a ziplock bag. For millennia, people used gourds, clay pots, baskets, or the internal organs of animals as containers to store precious food and water, but the utility of these containers pales in comparison to a strong, watertight bag made of polyethylene that is durable, transparent, thinner than a human hair, physically robust, nearly weightless, and can be used for years and years. However, we now use so many plastic bags, wraps, and containers that they have become a serious environmental nuisance.

We will see that, like many other things, the element carbon has both positive and negative potentials and attributes. The mining and use of coal and oil and even the inhalation of campfire soot has serious consequences on both present and past human health. The burning of fossil fuels has led to a buildup of carbon dioxide that is creating a frenzy of concern over human-induced global warming and sea level rise. Radioactive carbon-14 (^{14}C), which is made naturally by cosmic rays impacting nitrogen at the top of the atmosphere and also by nuclear bomb tests, provides a fantastic means to date events since the dawn of civilization, but, like coal, it also has side effects. Half of the radioactivity inside our bodies, a whopping four thousand disintegrations each second, is due to the decay of carbon-14. It is amazing to consider that a concentration of carbon atoms from our bodies can make a Geiger counter run off the scale, and that radioactive carbon made at the edge of the atmosphere as well as normal carbon are utilized in building the structure of plants that are ultimately eaten by us. The other half of our internal radioactivity comes from the decay of natural potassium in our bones. Although this radioactivity sounds alarmingly bad, the decay of carbon-14 in DNA has been proposed to play a possible role in genetic mutations that allow species to evolve over long time scales.

Our investigation of the sixth element will take us into these and other ethical aspects of its uses, and into the laboratories of great scientists—physicists, chemists, astronomers, biologists—who have contributed to our understanding of carbon and of what an element actually is, which played a crucial role in the history of science. It took scientists, or natural philosophers as they were once called, many centuries to figure out what an element is. At first, this could be done only by characterizing its behavior: if a particular substance always acted the same way in chemical reactions and could not be broken down into subordinate materials with different properties, then it was deemed to be an element. Only later was the link between element identity, atoms, and atomic structure understood.

The wondrous element carbon has truly shaped "our world" in the grandest sense that encompasses the origin and evolution of biology on Earth and extends to myriad nuclear and chemical processes that have and will occur over the entire spatial and time scale of the cosmos.

INDEX

Page numbers in italics refer to figures

absorption lines, 110, 113, 155, 207
acetylene, 136
alchemy, 35
alcohol, 147
Allan Hills 84001 meteorite, 104
Allen, Woody, 219
allotropes, 43
alpha particles, 21, 26, 54
Alpher, Ralph A., 18–20, 221n3
amber, 144
amino acids: glycine, 42–43, 81; handedness of, 89–90; life and, 42, 48–50, 71, 80–81, 89–90; Miller-Urey experiment and, 89–90; RNA and, 90
ammonia, 75–76, 89
amorphous carbon, 47, 115
Andromeda Galaxy (M31), 202–3, 225n1
Angola, 174
anisotropy, 44
Antares, 204
anthropic principle, 20–22
antifreeze, 146–47
argon, 38–39, 196
Aristarchus of Samos, 51
Arnold, Philip, 172
Arrhenius, Svante, 72, 98
Asimov, Isaac, 101
asphalt, 5, 48, 138
asteroids: carbon and, 17, 60–62, 65, 87, 92; diamonds and, 168–70; dinosaurs and, 84, 87; formation of, 56–67; life and, 84, 87, 92; nitrogen and, 17
astrobiology, 70, 85, 93, 117
astrology, 35, 222n1
astronomy, 147; Alpher and, 18–19, 221n3; amateur, 151; astrology vs., 35; Baade and, 202, 225n1; Barnard and, 106, *107*, 121, 224n5; Bethe and, 19, 221n1; Big Bang and, 17 (*see also* Big Bang); Brownlee and, 81–82; carbon and, 3, 8, 17, 29, 32, 51, 62, 91, 110–11, 113, 126, 151, 218–19, 223n2; chemistry and, 35, 46; Copernicus and, 51, 53; Drake and, 126; galaxies and, 202–9; Gamow and, 18–19, 221n3; glycine and, 81; Hall and, 100; Herschel and, 9, 25, 29; Hoyle and, 19–23, *24*, 73, 90–91; Hubble and, 202, 206, 219, 223n1; International Astronomical Union and, 62; Kuiper and, 61; life and, 81, 91,

astronomy (*continued*) 100–101, 105; Lowell and, 62, 101; Mayor and, 121; Milky Way and, 106, 110–21, 126; Oort and, 61; Queloz and, 121; Reber and, 113; Russell and, 30–31; Sandage and, 206–8; Scheiner and, 91; Schiaparelli and, 100; Shapley and, 30–31; solar mass and, 23–28; spectra and, 29–30 (*see also* spectra); Struve and, 32; telescopes and, 218 (*see also* telescopes); time scales and, 193; Tombaugh and, 62, 222n3; Trumpler and, 106–7. *See also* stars
atmosphere: average temperature and, 182–201; carbon in, 6–8, 27, 59–63, 66, 68, 70, 76–79, 87, 92, 99, 104, 106, 109, 111, 133, 135, 149, 170, 181, 184–85, 186–93, 197–201, 216–17, 224n1; carbon-silicate cycle and, 186–87; Earth's, 26, 49, 55, 59–60, 63, 66, 68–82, 86–89, 92, 94, 99, 103, 108, 122–24, 144, 169, 181–93, 196–201, 217–18, 224n1; Keeling Curve and, 188–89; life and, 49, 59, 66–75, 79–88, 94, 99, 103, 122–23, 135, 181–83, 186, 188, 199, 201; lithosphere and, *67*, 68, 185; Mars and, 59, 63, 77, 86–87, 103–4, 166, 218, 224n1; stars and, 26–27, 68, 87, 106, 122, 124, 218; temperature of, 189–201; Venus and, 26, 63, 77, 87, 99, 183, 218
atomic bomb, 150
atomic mass, 37
atomic motion, 91
atomic nucleus. *See* nucleus
atomic number, 20
atomic structure, 8, 14, *41*
atomic theory, 13
atomic weight, 35
automobiles, 137–40

Baade, Walter, 202–3, 225n1
Baekeland, Leo, 143
Bakelite, 143
banded iron formations (BIFs), 78
Barnard, Edward Emerson, 106, *107*, 121, 224n5
Barnard's Star, 121
Barringer Meteor Crater, 162
basalt, 83, 94, 166
Beatles, 29
Benz, Carl, 137–38
beryllium, 15, 19–22, 151
beta decay, 19
Bethe, Hans, 19–20, 221n1
Big Bang: carbon and, 17–20, 32, 212–14; dark age and, 213; diamonds and, 166; galaxies and, 205, 209, *210*; Gamow and, 17–19; gravity and, 55–56, 213–14; helium and, 19–20, 32, 166, 212; Hoyle and, 20, 221n2, 222n2; hydrogen and, 18, 32, 212, 214; universal expansion and, 17–18, *210*, 214
Big Hole, 158, *159*
biology: age of Earth and, 53–54; astrobiology, 70, 85, 93, 117; carbon and, 4, 8, 16–17, 69, 75, 77, 85, 89, 92–93, 187, 217; chemistry and, 4, 8, 16–17, 70, 72, 77, 92, 117, 123; climate issues and, 187; DNA and, 8, 48–50, 73, 80–81; life and, 4, 17, 49, 54, 69–77, 83, 85, 89–93, 98, 123; Milky Way and, 117, 123
biosignatures, 122–23
Bissell, George, 128
Black Cloud, The (Hoyle), 73

black dwarfs, 216
black holes: event horizon and, 211, 225n3; gravity and, 25, 211, 214–15, 225n3; light and, 211, 214, 225n3; mass and, 25, 96, 205, 209–11, 214–15, 218, 225n3; supermassive, 209; supernovae and, 25, 96, 215
blood diamonds, 174
Boeing 787 Dreamliner, 152–53
Bogart, Humphrey, 180
Bohr, Niels, 37
BPM 37093, 29, 170
Brackett, Leigh, 101
Bradbury, Ray, 101
Brownlee, Don, 81–82
Bruno, Giordano, 121
B²FH paper, 23, *24*
Buckminsterfullerene (buckyballs), 3, 45–47, 118
Burbidge, Geoffrey, 23, *24*
Burbidge, Margaret, 23, *24*
Burroughs, Edgar Rice, 101–2
Butler, Paul, 122

caffeine, 33–34
calcium, 29, 42, 116, 136, 141–42, 186
californium, 221n1
Caltech, 20, 22, 55, 206, 221n5
Cambrian explosion, 83–84
Cambridge University, 30, 205
canaries, 224n2
cancer, 48, 156
carbon: abundance of, 1, 3, 16–17, 32, 39, 54, 56, 59–65, 70, 76–77, 85, 104, 108, 113, 119, 126, 141, 149, 182–85, 192, 193, 213–14; amorphous, 47, 115; asteroids and, 17, 60–62, 65, 87, 92; astronomy and, 3, 8, 17, 29, 32, 51, 62, 91, 110–11, 113, 126, 151, 218–19, 223n2; atmospheric, 6–8, 27, 59–63, 66, 68, 70, 76–79, 87, 92, 99, 104, 106, 109, 111, 133, 135, 149, 170, 181, 184–93, 197–201, 216–17, 224n1; atomic structure of, 1, 14–15; atomic weight of, 2; Big Bang and, 17–20, 32, 212–14; biology and, 4, 8, 16–17, 69, 75, 77, 85, 89, 92–93, 187, 217; bonds of, 2–4, 7, 15, 27, 34, 38–42, 45, 47, 50, 66, 77, 91, 140, 142, 145, 156, 160; caffeine and, 33–34; charcoal and, 4, 11–13, 60, 141; in C IV state, 207, 209; as coke, 141; comets and, 17, 60–61, 65, 92; dating by, 149–52; Deep Carbon Observatory (DCO) and, 199–200; discovery of, 2, 9–18; dust and, 1, 23, 46, 51–52, 57, 64–66, 92, 102, 108, 113, 116, 137, 141, 143, 156, 181, 193, 198, 211, 215; electrons and, 1–2, 15–19, 38–42, 47, 54, 110, 113, 128, 156, 207, 212, 215, 223n2; as element, 13; food and, 6–7, 94, 103, 128, 147, 149, 181, 186, 194; formation of, 18–25, 221n1; future uses of, 217–19; graphite and, 3 (*see also* graphite); hydrogen bonds and, 2, 7, 34, 38, 42, 47, 77; isotopes of, 18, 35–37, 54, 149–51; Lavoisier and, 9–18, 33, 71; life and, 69–71, 75–80, 85–94, 99, 102–4; lonsdaleite and, 161–62; Mars and, 5, 17, 39, 48, 59, 63, 77, 102, 104, 219, 224n1; Moon and, 5, 17, 39, 61–62, 69, 92–93; nanotubes of, 2–3, 47, 153, 156; neutrons and, 2, 15, 18–20, 25, 54, 149, 215; nucleic acids and, 80; nucleus and, 1, 15, 19, 22, 37–38, 40; protons and, 1–2, 15, 18–20, 37–38, 54, 149, 215; rarity of, in Earth's interior, 1; solar system and, 1, 17, 39, 51,

carbon (*continued*) 57–61, 64–65, 68, 92–93, 106, 119, 126, 170, 199, 204, 217; spectrum of, 45, 85, 102, 108–10, 118, 150, 207, 223n2; steel and, 5, 138, 140–42, 148, 152, 154, 178–79; Sun and, 1, 6–7, 16, 23–29, 32, 56–66, 70, 76–77, 94, 99, 113, 134, 148, 151, 160–61, 185, 187, 204, 207, 213, 215–18; three-body reaction sequence and, 20–23; uses of, 127–56; Venus and, 5, 17, 39, 63, 77, 99, 183; wonders of, 1
carbon-12, 37
carbon-13, 37
carbon-14, 7–8, 37, 54, 103, 149–51, 222n2
carbon capture and storage (CCS), 133
carbon chains, 2, 43
carbon dioxide: buildup of, 4; climate issues and, 7, 131, 140, 182–84, 186–201; coal and, 131–33; concrete production and, 6; Copernicus Anthropogenic Carbon Dioxide Monitoring and, 199; diamonds and, 160–61, 167; Earth's temperature and, 182–87, 189–201; fossil fuels and, 7, 55, 140, 150, 187, 189, 198; Great Dying and, 185; as greenhouse gas, 77, 197–98; growth of atmospheric, 188–89, 193–201; inhaling, 194; James Webb Space telescope and, 68; Keeling Curve and, 188–89; Lavoisier and, 11–13, 216; life and, 76–79, 87, 92; Mauna Loa Observatory and, 188; steel and, 140; volcanoes and, 87, 167, 186
carbon epoxy, 153
carbon fibers, 152–53
carbonic acid, 186, 197
Carboniferous Period, 130–31
Carbon Mineral Challenge, 200
carbon monoxide: canaries and, 224n2; chemistry and, 47; Earth and, 57, 61–64; steel and, 140–41
carbon sheets, 3, 45–47
carbon tax, 4
Carrington Event, 151
Catholic Church, 53, 121, 221n2
Cavendish, Henry, 71
cellulose, 142, 224n3
cement, 141–42
Cenozoic Era, 127
Ceres, 62
Chandrasekhar limit, 215
charcoal, 4, 11–13, 60, 141
Charon, 62
chemical vapor deposition (CVD), 178
chemistry: alchemy and, 35; allotropes and, 43; and anisotropy, 44; astronomy and, 35, 46; biology and, 4, 8, 16–17, 70, 72, 77, 92, 117, 123; caffeine and, 33–34; carbon monoxide and, 47; carbon-silicate cycle and, 186–87; coal and, 43, 48, 50; compounds, 2–6, 16–17, 32–34, 39–40, 59, 64, 66, 74, 79, 84, 90–93, 104, 137, 146, 160, 162, 182, 200; and covalent bonds, 40, 42, 145; decay and, 53–55, 58; diamonds and, 158–60; and double bonds, 42, 45, 47; electrons and, 14–15, 37–44, 47, 222n2; electrostatic bonds, 40, 42; fullerenes and, 3, 45–47, 118; graphite and, 43–46; helium and, 38; hydrogen and, 34, 38, 42–43, 47–48; ionic bonds and, 40–42; isotopes and, 35–37; kids' sets of, 34; Lavoisiers and, 9–17; life and, 39–40, 103; mass

and, 37, 39, 44–49; Mendeleev and, 35; methane and, *41*; neutrons and, 35, 37; nitrogen and, 34, 42–43; nuclear energy and, 8, 15; oxygen and, 34; periodic table, 35, *36*; polymers, 5, 80, 142–45, 152; popular conception of, 34–35; protons and, 35–38; safety regulations and, 222n1; and siderophile character, 66; silicon and, 39; spectra and, 45–46; three-body reaction sequence and, 20–23; triple bonds, 42, 50, 156; uses of carbon and, 127–56; *Viking* landers and, 103; water and, 35, *41*
Chernobyl nuclear disaster, 134–35
China, 73, 100, 134, 141, 154, 198
chiral molecules, 89–90
chlorine, 40, *41*, 151
chlorofluorocarbons, 184
Clarke, Arthur C., 101
clay, 5, 7, 90, 154
climate issues: average temperature of Earth and, 182–86, 189–201; biology and, 187; carbon dioxide and, 7, 131, 140, 182–201; carbon-silicate cycle and, 186–88; and carbon tax, 4; chlorofluorocarbons and, 184; coal and, 131–33; environmental issues and, 184–85, 188, 201; evolution and, 188; fossil fuels and, 7, 140, 187, 190, 194, 197; and glaciers, 88, 131, 188–95; Great Dying and, 185; greenhouse gases and, 183, *196*, 197–98; habitability and, 6, 84–86, 181, 184, 199; ions and, 186; Keeling Curve and, 188–89; and Mars, 184, 185; meteorites and, 188, 200; methane and, 185, 190, 197, 200; nitrogen and, 196; oxygen and, 185–87, 196, 198, 199; polar ice and, 4, 101, 190, *191*; and sea levels, 4, 7, 189, 194–95; Venus and, 184, 185; volcanoes and, 70, 87, 99, 186, 193; water and, 186, 194–99; and weather, 4, 194
CLIPPIR diamonds, 164
coal: chemistry and, 43, 48, 50; depletion of, 75; environmental issues and, 131–34; extraction methods for, 133; as fossil fuel, 127–36; grades of, 132–33; light from, 136; mining of, 7, 131–34; steel and, 141; transportation and, 137–40
coal tar, 5
cocktails, 146–47
coke, 141
combustion, 161; fossil fuels and, 133, 137; Lavoisier and, 11–13, 16, 216; phlogiston and, 11–13, 32, 71
comets: alcohol and, 147; carbon and, 17, 60–61, 65, 92; formation of, 56, 59–61, 65; glycine and, 81; life and, 81, 92; nitrogen and, 17
compounds: chemistry and, 2–6, 16–17, 32–34, 39–40, 59, 64, 66, 74, 79, 84, 90–93, 104, 137, 146, 160, 162, 182; diamonds and, 160, 162; life and, 74, 79, 84, 90–93, 104
concrete: clay and, 5; environmental issues and, 5–6, 141–42, 178–79; formation of, 5–6; lime as component of, 5, 141–42; production of, 5–6
constellations, 28, 106, *206*, 225n3
Copernicus, Nicolaus, 51, 53
Copernicus Anthropogenic Carbon Dioxide Monitoring (CO_2M), 199
Copernicus program, 199
Cornell University, 14
cosmic rays, 7, 72, 149, 214

covalent bonds, 40, 42, 145
COVID-19, 73, 156, 194
Crater of Diamonds State Park, 168–69
Crown Jewels, 164
Crutzen, Paul, 188
crystals: diamonds, 3, 28, 157–62, 165–66, 170, 216; fullerenes as, 3, 45–47, 118; quartz, 46, 90, 178
Cullinan diamond, 164
Curl, Robert, 45
CVD (chemical vapor deposition), 178
cyanonaphthalene, 119
cyanopentaacetylene, 119

dark age, 213
De Beers, 174–75
decay: beta, 19; chemistry and, 53–55, 58; electrons and, 18–19, 54; gamma rays and, 22; neutrons and, 18; nucleus and, 18; plutonium and, 221n1; protons and, 18–19, 54, 221n1; radioactivity and, 7–8, 53–54, 149–50, 166, 185, 197; uranium and, 53–55, 221n1
Declaration of Independence, 5
Deep Carbon Observatory (DCO), 199–200
Deepwater Horizon, 130
del Rey, Lester, 101
de Mestral, George, 146
Democratic Republic of Congo, 174
density: Chandresekar limit and, 215; diamonds and, 28–29; Earth and, 67, 108; gases and, 23, 30, 58, 111; gravity and, 58, 215; Milky Way and, 108, 110–11, *112*; nuclear reactions and, 21; and solar mass, 23–28; stars and, 23, 28, 30, 110, 213, 215; Titan, 62; universal expansion and, 73, 213
diamonds, 1; asteroids and, 168–70; Big Bang and, 166; Big Hole and, 158; black, 161; blood, 174; BPM 37093, 29; burning of, 13; carbon dioxide and, 160–61, 167; chemistry of, 158–60; CLIPPIR, 164; compounds and, 160, 162; as crystals, 3, 28, 157–62, 165–66, 170, 216; cutting of, 175–76; dark side of, 171–74; De Beers and, 174–75; density and, 28–29; dust and, 160, 175; electronics and, 179; enhancement of, 179–80; formation of, 162–63; graphite and, 158–62; helium and, 166–67; historical perspective on, 157–58; Hope Diamond, 161, 171; HPHT (high pressure and high temperature), 177–78; hydrogen and, 165; industrial, 177–79; iron and, 165–66; Koh-i-Noor, 171; Lavoisier and, 13, 161, 216–17; Lesedi La Rona, 163; light and, 170, 175–76; lonsdaleite and, 161–62; magnesium and, 165; Mantle Transition Zone (MTZ) and, 164–65; meteorites and, 160–62, 165–66, 168–70; methane and, 165; mining of, 158, 172–74; Mohs hardness scale and, 178; nitrogen and, 162–63; oxygen and, 165; properties of, 159–60; salted fields of, 172–73; silicon and, 165, 179; solar system and, 164, 170; South Africa and, 157–58; sparkle of, 175–76; superdeep, 164–66; surgical, 179; synthetic, 176–78; telescopes and, 179; types of, 161–64; uses of, 157, 160–61; volcanoes and, 158, 167–69; water and, 165–67; white dwarf of, 28–29, 170, 216
diffuse interstellar bands (DIBs), 117–19

dinosaurs, 84, 87, 98, 190–91, 200–201
disks, 51, 56–58, 63–64, 120, *123*
DNA, 8, 73; amino acids and, 48–50, 80–81; double helix of, 48, 80; as polymers, 5, 80, 142–45, 152; proteins and, 48–50, 80–81
Doppler shift, 122, 124, 204–9, 212–13
Dordogne region, 5
double bonds, 42, 45, 47
double helix, 48, 80
Drake, Edwin, 128
Drake, Frank, 126
Drake equation, 126
Draugr (exoplanet), 121
Drew, Richard, 144–46
"duck tape," 144–46
duct tape, 145
DuPont, 145
dust: carbon and, 1, 23, 46, 51–52, 57, 64–66, 92, 102, 108, 113, 116, 137, 141, 143, 156, 181, 211, 215; cosmic, 65–66, 175, 215, 225n3; diamond, 160, 175; Earth and, 51, 52, 55–58, 64–66; gold, 172; interstellar medium (ISM) and, 107–13, 116–18; life and, 72–73, 92, 102; light and, 52, 72, 102, 107–8, 113–15, 156, 211, 225n3; Milky Way and, 106–8, 111, 113–17, 120; polycyclic aromatic hydrocarbons (PAHs) and, 48; stars and, 1, 23, 51–52, 56, 58, 64, 106–8, 111–16, 120, 129, 211, 215, 225n3
dwarf planets, 61–62, 222n3

Earth: age of, 53–56; atmosphere and, 26, 49, 55, 59–60, 63, 66, 68–82, 86–89, 92, 94, 99, 103, 108, 122–24, 144, 169, 181–93, 197–201, 217–18, 224n1; carbon dioxide and, 5; carbon monoxide and, 57, 61–64; chemistry and, 35–39, 43, 49; composition of, 29–32; core of, 66–67, 92, 166, 200, 217; crust of, 54, 66–67, 166, 185–86, 200; density and, 67, 108; dust and, 51, 52, 55–58, 64–66; environmental issues and, 6 (*see also* environmental issues); erosion and, 54; evolution of, 3, 8; formation of, 56–65; fossil fuels and, 55, 77, 127–36; future of, 217–19; as garden planet, 199; geocentric model and, 51; gravity and, 86, 213, 218, 225n3; habitable zone and, 87, 94–97, 124, 217; helium and, 54, 56, 59; hydrogen and, 56, 59; interior structure of, 66–68; iron and, 56–57, 66–67; isotopes and, 54–55; life and, 69–105 (*see also* life); light and, 136–37; magnesium and, 56; mantle of, 66–67, 124, 162–66, 217; Mantle Transition Zone (MTZ) and, 164–65; mass and, 54–60, 64–66; nitrogen and, 56–57, 59, 62, 63; nuclear energy and, 8; origin of, 49; oxygen and, 56; ozone and, 76, 99, 122, 184, 190; Rare Earth Hypothesis and, 81–82; sedimentation and, 54, 130, 150, 186; silicon and, 56, 64; spin axis of, 86, 192; temperature of, 182–87, 189–201; tides and, 86
earthquakes, 68, 133, 142
Edison, Thomas, 136
Edscottite, 200
electric cars (EVs), 138, 140
electromagnetism, 109
electronics: books and, 155; chemistry and, 47; communication and, 128; diamonds and, 179; gas monitors, 224n2; graphene and, 45; graphyne

electronics (*continued*) and, 156; Information Age and, 156; and radio astronomy, 113; smell of, 143; transportation and, 138; vacuum tubes and, 143
electron pairs, 40, 42
electrons: bonds and, 2, 38–42, 47, 156, 222n3; carbon and, 1–2, 15–19, 38–42, 47, 54, 110, 113, 128, 156, 207, 212, 215, 223n2; charge of, 14; chemistry and, 14–15, 37–44, 47; decay and, 18–19, 54; energy levels of, 22, 37–38; excited states and, 22, 110; galaxies and, 207, 212, 215; helium and, 1, 14, 16, 38, 54, 212; hydrogen and, 1–2, 14, 18, 38, 47, 113, 212; iron and, 207; light and, 110; magnesium and, 207; nucleus and, 1, 14–16, 19, 37–40, 113; oxygen and, 1, 207; Pauli exclusion principle and, 37–38; quantum state and, 16, 37–38, 215, 222n2; silicon and, 39, 179, 207; valence, 39–40
electron shells, 22; chemistry and, 37–40, 47, 222n2; nucleus and, 16
electrostatic bonds, 40
elements: Alpher-Bethe-Gamow theory and, 18–20; atomic structure and, 14; compositions of, 29–30; formation of, 18–20; natural forms of, 2, 15, 43; three-body reaction sequence and, 20–21. *See also specific element*
Elizabeth II (queen), 45
emission lines, 81, 110–11, 207, 221n4
energy levels, 22, 37–38
environmental issues: average temperature of Earth and, 182–87, 189–201; climate as, 184–85, 188, 200–201; coal and, 131–34; concrete and, 5–6, 141–42, 178–79; fossil fuels and, 55, 77 (*see also* fossil fuels); habitability and, 6, 84–86, 181, 184, 199; lead and, 34, 45, 55, 63, 99; life and, 70, 82, 92–93; mines and, 7, 128, 131–35, 158, 172–74, 224n2; oil spills as, 130, 224n1; ozone, 76, 99, 122, 184, 190; Paris Agreement and, 198; plastics and, 6–7, 137, 142–49, 152; polar ice, 4, 101, 191, *191*; pollution as, 6, 34, 48, 131, 134; radioactivity as, 135; and sea levels, 4, 7, 189, 194–95; uses of carbon and, 130, 133–34; water and, 184–85, 194–99; and weather, 4, 194
erosion, 54
European Space Agency, 199
European Union, 198
event horizon, 211
Event Horizon Telescope (EHT), 225n3
evolution: of atmosphere, 188; Earth and, 3, 8; Haldane on, 75; life and, 38, 54, 64, 69, 74–79, 83, 86–91; materials science and, 152; Oparin on, 74–75; societal, 134–35, 152, 154, 174; stellar, 14, 23, 212, 216–19
EVs (electric cars), 138, 140
excited states, 22, 110
exclusion principle, 37–38
exogenesis theory, 72–73, 98, 183
exoplanets: detection of, 121–22; Drake equation and, 126; formation of, 60; life and, 68; Milky Way and, 119–26; Transiting Exoplanet Survey Satellite (TESS) and, 124
extinction: curve of, 115; interstellar, 108; of life, 79, 83–88, 184–85, 188, 200–201

extremophiles, 82–83, 93–94
Exxon Valdez, 130

Ferme générale, 13
fertilizers, 128
Feynman, Richard, 38
51 Pegasi, 121–22
Finland, 4
fission, 54, 134
food: caffeine and, 33–34; carbon and, 6–8, 94, 103, 128, 147, 149, 181, 186, 194; chain of, 149, 181; containers for, 147; energy from, 224n3; fertilizer and, 128; Keeling Curve and, 188–89; life and, 89, 94, 103; polycyclic aromatic hydrocarbons (PAHs) and, 48; smell of, 89
Ford, Henry, 138
fossil fuels: burning of, 7, 77, 127, 133–34; carbon dioxide and, 7, 55, 140, 150, 187, 189, 198; cement and, 141–42; climate issues and, 7, 55, 77, 127–36, 140–42, 150, 181, 185, 189, 195, 198; coal, 7, 43, 48, 50, 75, 127–41; developing industry of, 128–30; Earth and, 55, 77, 127–36; environmental issues and, 7, 55, 77, 127–36, 140–42, 187, 190, 194, 198; exhaustion of, 134; and fracking, 130; natural gas, 77, *128*, 130, 133–34, 136; oil, 7, 127–36, 138, 148, 224n1; steel and, 140; subterranean reservoirs of, 181
fossils, 54, 75, *76*, 83, 88, 104
Fourier, Joseph, 182, 219
Fowler, William "Willie," 22–23, *24*
fracking, 130
Franklin, Rosalind, 48, 219
Fraunhofer lines, 29–30
French Academy of Sciences, 13
French Revolution, 9, 14
Freon, 145
Fukushima nuclear disaster, 134–35
Fuller, Buckminster, 3, 45, 118, 222n5
fullerenes, 3, 45–47, 118
fusion, 18, *27*, 78, 135

galaxies: astronomy and, 202–9; Big Bang and, 205, 209, *210*; electrons and, 207, 212, 215; gravity and, 202–3, 211; habitable zone (HZ) and, 97; helium and, 204; Hubble and, 202; hydrogen and, 204, 207; light and, 202–13; magnesium and, 207; mass and, 203, 205, 209, 213–18; oxygen and, 207; panspermia hypothesis and, 72–73, 98, 183; redshift and, 204–9, 212–13; silicon and, 207; spectra and, 205–7; telescopes and, 202–6, 209, 218; universal expansion and, 205, 209–14
galena, 45
Galilei, Galileo, 121
gamma rays, *21*, 22, 109, 111
Gamow, George, 17–20, 221n3
gas giants, 59, *125*
gasoline additive, 145
Geiger counters, 8
Geim, Andre, 44, 222n4
geocentric model, 51
Georgetown University, 18
germ theory, 72
glaciers, 88, 131, 188–95
globular clusters, 203–4
glycine, 42–43, 81
gold, 66, 171–74, 179
Goodyear, Charles, 147–48
Gore, Al, 195
graphene, 3, 43–45, 156, 159

graphite: chemistry and, 43–46; crystalline, 158; diamonds and, 158–62; fibers of, 6, 152; Lavoisier and, 11–13; Milky Way and, 115–16, 126; pencils and, 3
graphyne, 156
gravitational waves, 25
gravity: Big Bang and, 55–56, 213–14; black holes and, 25, 211, 214–15, 225n3; density and, 58, 215; Earth and, 86, 213, 218, 225n3; galaxies and, 202–3, 211; law of, 9; Moon and, 59, 86; motion and, 9; Newton and, 35; solar system and, 9, 55–56, 59, 86; stars and, 25, 27, 202–3, 211–15, 218; Sun and, 9, 55–56, 59, 60; supergiants and, 27; tides and, 86
Great Diamond Hoax, 171–72
Great Dying, 185
Great Oxidation Event (GOE), 77, 79
Greeley, Horace, 172
greenhouse gases (GHGs): average temperature and, 182–87, 189–201; carbon dioxide, 77, 198; chlorofluorocarbons as, 184; climate issues and, 183, *196*, 198; fossil fuels and, 7, 55, 77, 127–36, 140–42, 150, 181, 187, 190, 194, 198; life and, 77; methane, 184–85, 190, 197, 199; ozone, 76, 99, 122, 184, 190
Greenstein, Jesse, 221n5
Gulliver's Travels (Swift), 223n3

habitability: environmental issues and, 6, 84–86, 181, 184, 199; and habitable zone, 87, 94–97, 124, 217–18
Haldane, J.B.S., 75, 223n1
half-life, 54, 149, 222n2
Hall, Asaph, 100
halos, 203–4
Hansen, James, 195
Harvard College Observatory, 30, *31*
Hawking, Stephen, 219
Hazen, Robert, 200
Heger, Mary Lea, 116
Heinlein, Robert A., 101
helium: abundance of, 1, 16, 31, 56, 59, 70, 166; alpha particles and, 21, 26, 54; Alpher-Bethe-Gamow theory and, 19; Big Bang and, 19–20, 32, 166, 212; chemistry and, 38; diamonds and, 166–67; Earth and, 54, 56, 59; electrons and, 1, 14, 16, 38, 54, 212; fusion and, 27, 78; galaxies and, 204; isotopes and, 18, 166; life and, 70, 75, 78, 96; Milky Way and, 116; neutrons and, 19–21, 54, 166; nucleus and, 1, 14, 16, 19–22, 54; Payne and, 30–31; protons and, 1, 14, 19–21, 54; shell of, 16, 26, 38; stars and, 1, 26, 31–32, 96, 204, 213; Sun and, 1, 25–26, 31–32, 56, 59, 70, 78, 96, 166, 213; three-body reaction sequence and, 20–23
Hepburn, Audrey, 178
Herschel, William, 9, 25, 29
Hodge, Paul, 221n5
Högbom, Arvid, 182
Holocene, 188
Hooker telescope, 225n1
Hope Diamond, 161, 171
Hoyle, Fred, 219, 222n2; Alpher-Bethe-Gamow theory and, 19–20; anthropic principle and, 20–22; astronomy and, 19–23, *24*, 73, 90–91; background of, 20; Big Bang and, 20, 221n2; B^2FH paper and, 23, *24*; Fowler and, 22–23, *24*; life and, 73, 90–91; nuclear energy and, 20, 22–23;

panspermia and, 73; spore theory and, 73; steady-state theory of, 73, 90–91; three-body reaction sequence and, 20–23
HPHT (high pressure and high temperature) diamonds, 177–78
Hubble, Edwin, 202, 206–7, 219, 223n1
Hubble's law, 209
Hubble Space Telescope (HST), 108, 120, 223n1
Huffman, Donald, 46
Hutton, James, 54
hydrogen: abundance of, 1, 16, 31, 56, 59, 70, 76, 108, 111, 113, 165, 214, 221n4; atomic structure of, 14–15; atomic weight of, 2; Big Bang and, 18, 32, 212, 214; carbon bonds and, 2, 7, 34, 38, 42, 47, 77; chemistry and, 34, 38, 42–43, 47–48; cosmic rays and, 149; diamonds and, 165; Earth and, 56, 59; electrons and, 1–2, 14, 18, 38, 47, 113, 212; Fraunhofer lines and, 29–30; fusion and, 27, 78, 135; galaxies and, 204, 207; isotopes of, 18; Lavoisier and, 13, 71; life and, 70–71, 75–80, 89, 94, 96; Milky Way and, 108, 111–13, 116–17, 124; nucleic acids and, 80; nucleus and, 1, 14, 38; Payne and, 30–31; protons and, 1–2, 14, 18, 38; shell of, 26, 47; spectrum of, 113, 117, 207, 221n4; stars and, 1, 25–27, 31–32, 47, 94, 96, 108, 111, 124, 135, 204, 207, 213–14; storage of, 153; Sun and, 1, 26, 29, 31–32, 56, 59, 70, 76, 78, 94, 96, 213; water and, 70
hydrogen cyanide, 42

IC348, 81
Ig Nobel Prize, 44, 222n4
Industrial Revolution, 1, 128, 137, 141, 181, 194
Information Age, 156
infrared light: improved telescopes and, 56; spectra and, 56, 81, 98, 108–9, 114, 122, 182–84, *197*, 225n3; Spitzer Space Telescope (SST) and, 81, 223n1
ink, 153–56
International Astronomical Union, 62
interstellar extinction, 108
interstellar medium (ISM), 107–13, 116–18
interstellar molecules, 113–19, 223nn2 and 3
Io, 61
ionic bonds, 40, 42
ions: carbon stages of, 223n2; chemistry and, *41*; C IV state, 207, 209; climate issues and, 186; Milky Way and, 108, 114, 117, 223n2; stars and, 221n4
iron: abundance of, 56, 78, 141, 165, 213; banded iron formations (BIFs), 78; coke and, 141; diamonds and, 165–66; Earth and, 56–57, 66–67; Edscottite, 200; electrons and, 207; ferrous, 78; fusion and, 27; life and, 78, 94; Milky Way and, 115–16; nuclear reactions and, 213; oxygen and, 140; pyroxene, 115; and siderophile chemicals, 66; stars and, 26–27, 32, 204, 213; steel and, 5, 138–42, 148, 152, 154, 178–79; Sun and, 26, 29, 32, 56–57, 66, 204, 207, 217
Iron Age, 140
isotopes: carbon, 18, 35–37, 54, 149–51; chemistry and, 35–37; Earth and, 54–55; helium, 18, 166; hydrogen, 18;

isotopes (*continued*)
lead, 55; neutrons and, 18, 35, 37, 54–55, 149–51, 166; Patterson and, 55; protons and, 18, 35, 37, 54–55, 149–51, 166; uranium, 54; uses of carbon and, 149–51
Ixtoc I oil spill, 130

James Webb Space Telescope (JWST), 68, 123, 204–5
jets, 120
Juína, Brazil, 164
Jupiter, 58–61, 80, 122–23, 170

Keeling Curve, 188–89
Kepler, Johannes, 53, 222n1
Kepler spacecraft, 124
Kimberley diamond mine, 158, 159
Kimberley Process, 174
kimberlite, 167
Kinetic Chemicals, 145
King, Clarence, 172–73
Kings Canyon, 173
Koh-i-Noor diamond, 171
Kola Superdeep Borehole, 67–68
Krätschmer, Wolfgang, 46
Kroto, Harry, 45, 219
Kuiper Belt, 61

lasers, 45, 177
last universal common ancestor (LUCA), 74
Late Cenozoic, 191
Late Heavy Bombardment (LHB), 69–70
lattices, 2, 43–44, 116
Lavoisier, Antoine, 219; and carbon as element, 12–13, 17, 33; carbon dioxide and, 11–13, 216; chemistry and, 9–17; combustion and, 11–13, 16, 216; death of, 13; diamonds and, 13, 161, 216–17; graphite and, 11–13; hydrogen and, 13, 71; instruments of, *13*, 14; Law of Conservation of Mass, 11; oxygen and, 11–13, 16, 71; phlogiston and, 11–13; "Reflections on Phlogiston," 13; scientific approach of, 11; water and, 13
Lavoisier, Marie-Anne Paulze, 9–14, 17, 219
Lavoisier's Law, 11. *See also* law of conservation of mass
law of conservation of mass, 11, 161
lead, 34, 45, 55, 63, 99
LEDs (light-emitting diodes), 137
Lemaître, Georges, 221n2
Lesedi La Rona diamond, 163
Lewis, C. S., 101
Libby, Willard, 149
Lick Observatory, 117, 122
life: amino acids and, 42, 48–50, 71, 80–81, 89–90; asteroids and, 84, 87, 92; astronomy and, 81, 91, 100–101, 105; atmosphere and, 49, 59, 66–75, 79–88, 94, 99, 103, 122–23, 135, 181–83, 186, 188, 198–99, 201; biology and, 4, 17, 49, 54, 69–77, 83, 85, 89–93, 98, 123; biosignatures and, 122–23; Cambrian Explosion and, 83–84; carbon and, 69–71, 75–80, 85–94, 99, 102–4; chemistry and, 39–40, 103; chiral molecules and, 89–90; comets and, 81, 92; compounds and, 74, 79, 84, 90–93, 104; and DNA, 8, 48–50, 73, 80–81; dust and, 72–73, 92, 102; environment needed for, 70, 82, 92–93; evolutionary theory and, 38, 54, 64, 69, 74–79, 83, 86–91; exogenesis

theory and, 72–73, 98, 183; exoplanets and, 68; extinction of, 79, 83–88, 184–85, 188, 200–201; extremophiles and, 82–83, 93–94; food and, 89, 94, 103; formation of, 70–76, 82–94; future of, 217–19; germ theory and, 72; Great Dying and, 185; greenhouse gases and, 77; habitability and, 6, 84–86, 181, 184, 199; habitable zone and, 87, 94–97, 124, 217; helium and, 70, 75, 78, 96; Hoyle and, 73, 90–91; hydrogen and, 70–71, 75–80, 89, 94, 96; iron and, 78, 94; and last universal common ancestor (LUCA), 74; Mars and, 77, 82, 86–87, 94–105; meteorites and, 81, 89, 103–4; methane and, 75–79, 89; microbial, 72, 77, 79, 82–85, 88, 93, 103–5, 201; Miller-Urey experiment and, 89–90; molecular machinery of, 70; nitrogen and, 70–71, 76, 80, 94; nucleic acids, 48, 80, 90; oxygen and, 6, 70–71, 75–82, 88, 92, 94; panspermia hypothesis, 72–73, 98, 183; Pasteur and, 72; photosynthesis and, 48–49, 75, 77, 94, 100, 198; Pluto and, 97; primordial soup theory, 74–75; proteins and, 48–50, 80–81, 89–90; Rare Earth Hypothesis and, 81–82; and RNA, 73–74, 80–81, 90–91; scientism and, 75; silicon and, 91–93; solar system and, 81–85, 88, 91–93, 96, 98; solvent for, 92–93; spore theory and, 72–73; steady-state theory of, 73, 90–91; Sun and, 6, 23, 25, 59–60, 64, 66, 70, 82–87, 94–100, 187, 200; telescopes and, 56, 68, 81, 100; Venus and, 77, 87, 97–101; water and, 70–71, 75, 77, 82–94, 98–104

light: absorption of, 29, 38, 47, 99, 109–10, 113, *115*, 116, 155, 183–84, *196*, 207, 212; bamboo filaments and, 136; and black holes, 211, 214, 225n3; coal and, 136; diamonds and, 170, 175–76; dust and, 52, 72, 102, 107–8, 113–15, 156, 211, 225n3; Edison and, 136; electrons and, 110; Fraunhofer lines and, 29–30; galaxies and, 202–7, 211–13; greenhouse effect and, 183; infrared, 56, 81, 98, 108–9, 114, 122, 182–84, *196*, 225n3; interstellar medium (ISM) and, 107–13, 116–18; Mars and, 102; Milky Way and, 107–10, 113–14, *115*, 122; nanotubes and, 47; Newton and, 35, 37–38; Pauli and, 37–38; photons, 38, 98, 109; photosynthesis and, 48–49, 75, 77, 94, 100, 198; Planck's constant and, 110; redshift and, 204–9, 212–13; reflection of, 62, 102, 176; refraction of, 176; Scotch tape and, 145; sensors of, 156; speed of, 109, 176, 207; stars and, 29, 32, 95, 105–8, 113–15, 122, 202, 207, 211–14, 218, 225n3; Sun and, 6, 29, 62, 99, 136, 161, 183, 187, 198, 216–18; transportation and, 138; ultraviolet, 46, 72, 76, 89, 99, 108–10, 115–18, 223nn1 and 2; visible, 109, 182, 212–13, 225n3; wavelength and, 29, 46, 107–10, 113–16, 156, 176, 182, 205–7, 212, 221n4, 223n1

light bulb, 155

light-emitting diodes (LEDs), 137

lighting, 94, 128, 136–37, 155

lightning, 89

light-years, 28, 105, 108, 223n2

limestone, 5, 63, 77, 141–42, 186–87, 193, 197

lithium, 15–16, 19, 30, 212
lithosphere, *67*, 68, 185
London International Exhibit (1862), 143
lonsdaleite, 161–62
Lowell, Percival, 101
Lowell Observatory, 62
Lucy (star), 29
Lyell, Charles, 54

Magna Carta, 5
magnesium: diamonds and, 165; Earth and, 56; electrons and, 207; fusion and, *27*; galaxies and, 207; Milky Way and, 115; nuclear reactions and, 213; stars and, 26, 32, 213; Sun and, 26, 32, 56, 207
Mantle Transition Zone (MTZ), 164–65
Marcy, Geoffrey, 122
Mariner 4 spacecraft, 102
Mars: Allan Hills 84001 meteorite and, 104; atmosphere of, 59, 63, 77, 86–87, 103–4, 166, 218, 224n1; canals of, 100–101; carbon and, 5, 17, 39, 48, 59, 63, 77, 102, 104, 219, 224n1; climate issues and, 184, 185; formation of, 58–64; life and, 77, 82, 86–87, 94–105; moons of, 86, 100; *Perseverance* and, 104; *Rosalind Franklin* and, 48; science fiction on, 101–2; spectra of, 102; Swift on, 223n3
mass: black holes and, 25, 96, 205, 209–11, 214–15, 218, 225n3; chemistry and, 37, 39, 44–49; conservation of, 11, 161; Earth and, 54–60, 64–66; elemental worthiness and, 15; galaxies and, 203, 205, 209, 213–18; Milky Way and, 108, 121–22, *125*; nucleus, 15–23, 54; solar, 23–28; solar system and, 108, 121–22, *125*; stars and, 23–28, 32, 57, 60, 95–97, 111, 114, 119–24, 203, 205, 213–18, 225n3; Sun and, 23, 25–29, 32, 56, 59–60, 97, 122, 161, 205, 209, 213–18, 225n3
mass extinction, 79, 84, 87, 200
mass number, 20
mass spectrometers, 150
Mauna Loa Observatory, 188
Mayor, Michel, 121
Mémoires de chimie (Lavoisier), 14
Mendeleev, Dmitri, 35
Mercury, 17, 26, 60, 218
Merrill, Paul, 117
Mesozoic Era, 127, 191, 200–201
metallic bonding, 222n3
Meteor Crater, 169
meteorites, 51, 200; age of Earth and, 55; climate issues and, 188; cosmic dust samples and, 65–66; COVID-19 and, 73; diamonds and, 160–62, 165–66, 168–70; glycine and, 81; life and, 81, 89, 103–4
methane: chemistry and, *41*; climate issues and, 184–85, 190, 197, 199; diamonds and, 165; as greenhouse gas, 132, 184–85, 190, 197, 199; life and, 75–79, 89; Milky Way and, 122–23; planet formation and, 57, 62–64; Pluto and, 57, *63*; Titan and, 62
methylidyne, 113, *114*
M4 (star cluster), 204
mica, 44
microorganisms: extremophiles and, 82–83, 93–94; life and, 72, 77, 79, 82–85, 88, 93, 103–5, 200
Milky Way: astronomy and, 106, 110–21, 126; biology and, 117, 123; density

and, 108, 110–11, *112*; dust and, 106–8, 111, 113–17, 120; exoplanets and, 119–26; formation of, 203–4; full-sky image of, *52*; graphite and, 115–16, 126; halo of, 203–4; helium and, 116; hydrogen and, 108, 111–13, 116–17, 124; interstellar medium (ISM) and, 107–13, 116–18; ions and, 108, 114, 117, 223n2; iron and, 115–16; light and, 107–10, 113–14, *115*, 122; magnesium and, 115; mass and, 108, 121–22, *125*; methane and, 122–23; nitrogen and, 123; oxygen and, 115, 117, 122–23, 136; silicon and, 115, 126; solar system and, 106, 119, 122–26; spectra and, 108–18, 122, 205; telescopes and, 106–9, 113, *114*, 118–23, 126; Transiting Exoplanet Survey Satellite (TESS) and, 124; water and, 122, 124

Miller, Stanley, 89–90

minerals: Carbon Mineral Challenge and, 200; Deep Carbon Observatory (DCO) and, 199–200; diamonds, 3, 157–80; Edscottite, 200; galena, 45; hydrous, 59, 61; Mars and, 103; mica, 44; Mohs scale and, 224n4; olivine, 115, 165; pyroxene, 115; quartz, 46, 90, 178; silicates, 65, 67, 87, 93, 115–16, 165, 185–87, 217; silicon carbide, 126; uranium dating of, 55; water-bearing, 59

mines, 224n2; coal, 7, 131–34; diamond, 158, 172–74; environmental issues and, 7, 128, 132–35, 158, 172–74; large-scale, 135; salt, 128

Mitchell, Joni, 1

Miyake, Fusa, 151–52

Mohs, Friedrich, 224n4

Mohs hardness scale, 178, 224n4

Monroe, Marilyn, 178

Moon: carbon and, 5, 17, 39, 61–62, 69, 92–93; craters of, 69; formation of, 39, 58; gravity and, 59, 86; Late Heavy Bombardment (LHB) and, 69–70; size of, 86; temperature of, 198–99; tides and, 86

motion: atomic, 91; Copernicus and, 51, 53; cyclic, 121; gravity and, 9; Newton and, 53; stars and, 51–53, 121, 225n3

Mount Wilson, 225n1

MTZ (Mantle Transition Zone), 164–65

nanotubes, 2–3, 47, 153, 156

naphthalene, 47

NASA, 100, 104, 144, 146, 195, 199, 204, 223n1

natural gas, 77, *128*, 130, 133–34, 136

Nature (journal), 188

nebulae: planetary, 25, 39, 56, 64–65; stars and, 25, 39, 56, 64–65, 106, 209, 221n4

neon, 26, 27, 38–39

Neptune, 59, 61, 170

neptunium, 221n1

neutrons: carbon and, 2, 15, 18–20, 25, 54, 149, 215; chemistry and, 35, 37; decay and, 18; helium and, 19–21, 54, 166; isotopes and, 18, 35, 37, 54–55, 149–51, 166; lack of charge of, 14; nitrogen and, 149

neutron stars, 25, 37, 121, 215

New Horizons spacecraft, 62, *63*

Newton, Isaac, 35, 37, 53, 154

nickel, 66, 165

nitrogen: abundance of, 17, 56, 62, 70–71, 76; asteroids and, 17; chemistry and, 34, 42–43; climate issues and, 195–96; comets and, 17; diamonds and, 162–63; Earth and, 56–57, 59, 62, *63*; life and, 70–71, 76, 80, 94; Milky Way and, 123; neutrons and, 149; nucleic acids and, 7; Sun and, 6, 56–57, 59, 62, 70, 76, 94; uses of carbon and, 149
Nobel Prize, 44, 45, 121, 195
noble gases, 16, 38–39
Novoselov, Kostya, 44
nuclear energy: advantages of, 134–35; bombs and, 7, 150; chemistry and, 8, 15; Chernobyl and, 134–35; Earth and, 8; fission, 54, 134; Fukushima and, 134–35; fusion and, 18, 27, 78, 135; Gamow and, 18; Hoyle and, 20, 22–23; reactors and, 25, 134–35; stars and, 20, 23–28, 213–16; Sun and, 25, 28, 78, 134, 213, 215
nucleic acids, 48, 80, 90
nucleus: carbon and, 1, 15, 19, 22, 37–38, 40; decay and, 18; electrons and, 1, 14–16, 19, 37–40, 113; helium and, 1, 14, 16, 19–22, 54; hydrogen and, 1, 14, 38; mass of, 15–23, 54; oxygen and, 1, 80, 213, 216; Rutherford and, 71

oil spills, 130, 224n1
OLEDs (organic light-emitting diodes), 6–7
olivine, 115, 165
On the Revolutions of the Heavenly Spheres (Copernicus), 51, 53
Oort, Jan, 61
Oparin, Alexander, 74–75
Orbiting Carbon Observatories, 199–200
organic light-emitting diodes (OLEDs), 6–7
"Origin of the Chemical Elements, The" (Alpher, Bethe, and Gamow), 221n3
Orion, 28, 106
Our Final Hour: A Scientist's Warning (Rees), 188
oxygen: abundance of, 1, 16, 56, 70–71, 78, 88, 165, 185, 213; carbon dioxide and, 149, 160–61, 167, 182–85; carbon fiber and, 152; chemistry and, 34; climate issues and, 185–87, 196, 197–98, 199; diamonds and, 165; Earth and, 56; electrons and, 1, 207; fusion and, 27; galaxies and, 207; Great Oxidation Event (GOE) and, 77, 79; iron and, 140; Lavoisier and, 11–13, 16, 71; life and, 6, 70–71, 75–82, 88, 92, 94; Milky Way and, 115, 117, 122–23, 136; nucleic acids and, 80; nucleus and, 1, 80, 213, 216; ozone, 76, 99, 122, 184, 190; Priestley and, 11; protons and, 1; stars and, 1, 26, 32, 122, 126, 213, 216; Sun and, 1, 6, 26, 32, 56, 70, 94, 187, 207
Oxygen Catastrophe, 77, 79
Oxygen Crisis, 77
Oxygen Revolution, 77
ozone, 76, 99, 122, 184, 190

PAHs. *See* polycyclic aromatic hydrocarbons
paleontology, 53, 81
panspermia hypothesis, 72–73, 98, 183
Paris Agreement, 198
Parkes, Alexander, 142–43
Parkesine, 143
Pasteur, Louis, 72, 90, 219
Patterson, Clair, 55, 219

Pauli, Wolfgang, 37–38
Payen, Anselme, 142
Payne(-Gaposchkin), Cecilia, 30–32
pencils, 3, 5, 34, 147, 153
Permian-Triassic extinction event, 185
Perseverance rover, 104
pesticides, 7
phlogiston, 11–13, 32, 71
Phobetor (exoplanet), 121
photons, 38, 98, 109–10
photosynthesis, 48–49, 75, 77, 94, 100, 198
Physical Review (journal), 221n3
Planck, Max, 37
Planck's constant, 110
plastics: amber as, 144; Bakelite, 143; cellulose and, 142, 224n3; environmental issues and, 6–7, 137, 142–49, 152; many uses of, 143; Parkes and, 142–43; societal effects of, 6–7; tape, 144–46; Teflon, 145; thermoplastics, 142; uses of carbon and, 6–7, 137, 142–49, 152; water and, 7, 143
Plastics Hall of Fame, 146
plastic state, 67
platinum, 66
Pliny the Elder, 157
Plunkett, Roy, 145–46
Pluto, 17; Charon and, 62; discovery of, 101; downgrading of, 222n3; formation of, 59, 62; life and, 97; methane and, 57, *63*, 123–24; *New Horizons* and, 62, *63*
plutonium, 54, 221n1
polar ice caps, 4, 101, 190, *191*
pollution, 6, 34, 48, 131, 134
Poltergeist (exoplanet), 121
polycyclic aromatic hydrocarbons (PAHs), 47–48, 115, 118, *119*, 205, 223n4
polymers, 5, 80, 142–45, 152
polytetrafluoroethylene (PTFE), 145
Pope, Gustavus, 98
Popigai crater, 162, 169
Population I stars, 203–4
Population II stars, 203–4
Population III stars, 204
Post-it notes, 145
potassium, 8, 53, 197
Priestley, Joseph, 11, 71
primordial soup theory, 74–75
Princess of Mars, A (Burroughs), 101–2
printing, 153–56
Proceedings of the National Academy of Sciences, 31
proteins, 48–50, 80–81, 89–90
protons: atomic structure and, 14–15; carbon and, 1–2, 15, 18–20, 35–38, 54, 149, 215; charge of, 14; chemistry and, 35–38; decay and, 18–19, 54, 221n1; helium and, 1, 14, 19–21, 54; hydrogen and, 1–2, 14, 18, 38; isotopes and, 18, 35, 37, 54–55, 149–51, 166; oxygen and, 1; stars and, 1, 215
protostars, 120
pyroxene, 115

quantum mechanics, 16, 37–38, 215, 222n2
quartz, 46, 90, 178
quasars, 206–9, 225n3
Queloz, Didier, 121

radar, 98–99, 138
radiation: Carrington Event and, 151; cosmic rays, 7, 72, 149, 214; gamma rays, *21*, 22, 109, 111; half-life and, 54, 149, 222n2; Miyake events and, 151–52; Planck's constant and, 110; solar flares and, 98, 151–52; X-rays, 72, 109–11, 171

radioactivity: carbon-13, 37; carbon-14, 7–8, 37, 54, 103, 149–51, 222n2; decay and, 7–8, 53–54, 149–50, 166, 185, 197; environmental issues and, 135; Geiger counter for, 8; plutonium and, 221n1; potassium, 53, 197; thorium, 53, 166; uranium, 15, 53–55, 134, 166, 221n; uranium and, 221n1
radiocarbon dating, 149–52
radio telescopes: black holes and, 205; chain molecules and, 118; improved methods of, 56; methylidine and, 113, *114*; Population III stars and, 204; quasars and, 206–9, 225n3; Reber and, 113
Rare Earth Hypothesis, 81–82
Rare Earth: Why Complex Life Is Uncommon in the Universe (Ward and Brownlee), 81–82
Reber, Grote, 113
red giants, 26, 97, 218–19
red light, 107–9, 212–13
redshifts, 204–9, 212–13
Rees, Martin, 188
"Reflections on Phlogiston" (Lavoisier), 13
Republic of Zimbabwe, 175
Review of Modern Physics (journal), 22–23, 24
Rhodes, Cecil, 174–75
ringwoodite, 165
RNA, 73–74, 80–81, 90–91
Rosalind Franklin rover, 48
rubber, 147–49
rubisco, 49
Russell, Henry Norris, 30–31
Rutherford, Daniel, 71

Sagan, Carl, 91, 97
Sagittarius, 225n3
Saha, Meghnad, 30
salt, 40–41, 128–29
salted diamond fields, 172–7
Sandage, Allan, 206–8
Saturn, 59, 62, 93, 124, 144, 170
Scheele, Carl Wilhelm, 71
Scheiner, Julius, 91
Schiaparelli, Giovanni, 100
Schmidt, Maarten, 207, *208*
scientism, 75
Scott, Edward, 200
Scripps Institution of Oceanography, 188
sea levels, 4, 7, 189, 194–95
sedimentation, 54, 130, 150, 186
Shapley, Harlow, 30–31
Sierra Leone, 174
silicates: carbon-silicate cycle and, 186–88; Earth's core and, 67, 217; life and, 93; Milky Way and, 115–16; plastic state and, 67; water and, 65, 165
silicon: abundance of, 39, 56, 165, 213; chemistry and, 39; diamonds and, 165, 179; Earth and, 56, 64; electrons and, 39, 179, 207; fusion and, 27; galaxies and, 207; life and, 91–93; Milky Way and, 115, 126; solvent for, 92–93; stars and, 26, 32, 64, 126, 213; Sun and, 32, 56, 64, 148, 207; uses of carbon and, 148
silicon carbide, 126
Silly Putty, 148–49
silver, 171
Slack, John, 172
Smalley, Richard, 45
smell, 89; chemistry and, 33–34, 47; electrical, 143; and polycyclic aromatic hydrocarbons (PAHs), 47–48, 115, 118, *119*, 205, 223n4

Smithsonian Museum of Natural History, 78
Snowball Earth, 79, 84, 184, 192–93, 201
snow line, 65
sodium, 29, 40, *41*
solar flares, 98, 151–52
solar mass, 23–28
solar system: age of, 55; carbon and, 1, 17, 39, 51, 57–61, 64–65, 68, 92–93, 106, 119, 126, 170, 198–99, 204, 217; chemistry and, 39; diamonds and, 164, 170; formation of, 53; geocentric model and, 51; gravity and, 9, 55–56, 59, 86; life and, 81–85, 88, 91–93, 96, 98; mass and, 108, 121–22, *125*; Milky Way and, 106, 119, 122–26; planetary formation and, 56–65; planets of, 17 (*see also specific planet*); plutonium and, 221n1; Rare Earth Hypothesis and, 81–82; Sun's disk and, 51, 56–58, 63–64
spectra: absorption lines, 110, 113, 155, 207; carbon, 45, 85, 102, 108–10, 118, 150, 207, 223n2; chemistry and, 45–46; diffuse interstellar bands (DIBs), 117–19; emission lines, 81, 110–11, 207, 221n4; Fraunhofer lines, 29–30; galaxies and, 205–7; Heger and, 116; Hubble Space Telescope (HST) and, 108, 223n1; hydrogen, 113, 117, 207, 221n4; infrared, 56, 81, 98, 108–9, 114, 122, 182–84, 196, 225n3; Mars and, 102; Merrill and, 117; Milky Way and, 108–18, 122, 205; of quasars, 206–7; radio, 85, 108–9, 113–14, 150, 206–7, 223n2; stars and, 29–30, 108, 114–15, 118, 122, 205, 207; Sun and, 29–30, 207; ultraviolet, 46, 72, 76, 89, 99, 108–18, 223nn1 and 2; universal expansion and, 205, 207; wavelength and, 29, 46, 107–10, 113–16, 156, 176, 182, 205–7, 212, 221n4, 223n1
speed of light, 109, 176, 207
Spitzer Space Telescope (SST), 81, 223n1
spore theory, 72–73
stars: atmospheres of, 26–27, 68, 87, 106, 122, 124, 218; black dwarf, 216; black holes and, 25, 96, 205, 209–11, 214–15, 218, 225n3; classification of, 30; clusters of, 106, 204; constellations of, 28, 106, *206*, 225n3; disks of, 51, 56–58, 63–64, 120, *123*; dust and, 1, 23, 51–52, 56, 58, 64, 106–8, 111–16, 120, 129, 211, 215, 225n3; formation of, 202; gravity and, 25, 27, 202–3, 211, 213–15, 218; helium and, 1, 26, 31–32, 96, 204, 213; hydrogen and, 1, 25–27, 31–32, 47, 94, 96, 108, 111, 124, 135, 204, 207, 213–14; in IC348 system, 81; ions and, 221n4; iron and, 26–27, 32, 204, 213; life of, 213–15; magnesium and, 26, 32, 213; mass and, 23–28, 32, 57, 60, 95–97, 111, 114, 119–24, 203, 205, 213–18, 225n3; metal-poor, 204; motion of, 51–53, 121, 225n3; nebulae and, 25, 39, 56, 64–65, 106, 209, 221n4; neutron, 25, 37, 121, 215; nuclear energy and, 20, 23, 25–28, 213–16; oxygen and, 1, 26, 32, 122, 126, 213, 216; Population I, 203–4; Population II, 203–4; Population III, 204; protons and, 1, 215; protostars, 120; red giant stage of, 26, 97, 218–19; silicon and, 26, 32, 64, 126, 213; spectra and, 29–30, 108, 114–15, 118, 122, 205, 207; supergiant, 26–27, *28*; supernovae and, 25–28, 96, 110–11, 114, 205, 209, 215; white dwarf, 11, 28, 37, 121, 170, 215–16

steady-state theory, 73, 90–91
steel, 152, 154; carbon monoxide and, 140–41; coal and, 141; coke and, 141; concrete and, 142; diamonds and, 178–79; fossil fuels and, 140; iron and, 5, 140–42; transportation and, 138, 148
stellar winds, 27, 106, 114
streaming instabilities, 58
Struve, Otto, 32
sulfur, 80, 84, 98–99, 148
Sun: age of, 23, 55, 213; Aristarchus and, 51; brightness of, 53, 77–79, 84, 96–97, 122, 124, 165, 185, 200, 217–18; carbon and, 1, 6–7, 16, 23–29, 32, 56–66, 70, 76–77, 94, 99, 113, 134, 148, 151, 160–61, 185, 187, 204, 207, 213, 215–18; Carrington Event and, 151; composition of, 29–32; Copernicus and, 51–52; density and, 23, 28, 30, 110, 213, 215; disk of, 51, 56–58, 63–64; energy from, 6, 25, 32, 78, 94, 99, 134, 183, 195–96, *196*, 213, 215, 218; expansion of, 84–85; future of, 217–18; gravity and, 9, 55–56, 59–60, 215, 218; heliocentric system and, 9, 51–53; helium and, 1, 25–26, 31–32, 56, 59, 70, 78, 96, 166, 213; Herschel and, 9, 29; hydrogen and, 1, 26, 29, 31–32, 56, 59, 70, 76, 78, 94, 96, 213; iron and, 26, 29, 32, 56–57, 66, 204, 207, 217; life and, 6, 23, 25, 59–60, 64, 66, 70, 82–87, 94–100, 187, 200; lifetime of, 23, 213; light and, 6, 29, 32, 62, 95, 99, 105–8, 113–15, 122, 136, 161, 183, 187, 198, 202, 207, 211–14, 216–18, 225n3; local bubble and, 111; magnesium and, 26, 32, 56, 207; mass and, 23, 25–29, 32, 56, 59–60, 97, 122, 161, 205, 209, 213–18, 225n3; nitrogen and, 6, 56–57, 59, 62, 70, 76, 94; nuclear energy and, 25, 28, 78, 134, 213, 215; oxygen and, 1, 6, 26, 32, 56, 70, 94, 187, 207; planet formation and, 56–64; as Population I star, 204; as red giant, 26; silicon and, 32, 56, 64, 148, 207; solar mass and, 23–28; spectra and, 29–30, 207; temperature and, 30, 57, 65–66, 78, 87, 111, 195–96, 218; Transiting Exoplanet Survey Satellite (TESS) and, 124; as white dwarf, 28
supergiants, 26–27, *28*
supernovae: black holes and, 25, 96, 215; nuclear states of, 27–28; stars and, 25–28, 96, 110–11, 114, 205, 209, 215
Swift, Jonathan, 223n3

tape, 144–46
tax farmers, 13
Teflon, 145, 224n4
telegraphy, 101, 151
telescopes: diamonds and, 179; Event Horizon Telescope (EHT), 225n3; galaxies and, 202–6, 209, 218; Hooker, 225n1; Hubble Space Telescope (HST), 108, 120, 223n1; James Webb Space Telescope (JWST), 68, 123, 204–5; life and, 56, 68, 81, 100; Milky Way and, 106–9, 113, *114*, 118–23, 126; nebulae and, 25; Newton and, 35; planet formation and, 56; radio, 56, 113, *114*, 118, 204–5, 225n3; Spitzer Space Telescope (SST), 81, 223n1; uses of carbon and, 152
TESS (Transiting Exoplanet Survey Satellite), 124
Texas Rangers, 130
Thomson, William (Lord Kelvin), 53

thorium, 53, 166
3C 48, 207
3C 273, 207
3M, 145
tides, 86
Tiffany & Co., 172, 178, 180
tires, 5, 138, 147–48
Titan, 62
titin, 49
Tombaugh, Clyde, 62, 222n3
Transiting Exoplanet Survey Satellite (TESS), 124
transportation, 137–40
transuranium elements, 221n1
TRAPPIST-1 system, 96
triple bonds, 42, 50, 156
Trumpler, Robert, 106–7
typewriters, 154–55

ultraviolet light: buckyballs and, 46; life and, 72, 76, 89, 99; Milky Way and, 108–18; spectra and, 46, 72, 76, 89, 99, 108–10, 115–18, 223nn1 and 2
United Nations, 174, 195, 198
United States Geological Survey (USGS), 173
universal expansion: Big Bang and, 17–18, *210*, 214; galaxies and, 205, 209–14; Hubble law and, 209; matter density and, 73; redshift and, 204–9, 212–13; spectra and, 205, 207
University of Chicago, 149
University of Colorado, 18
University of Hawaii, 200
uranium, 15, 53–55, 134, 166, 221n1
Uranus, 29, 59, 170
Urey, Harold, 89–90
uses of carbon: for cement, 141–42; for dating, 149–52; environmental issues and, 130, 133–34; for fibers, 152–53; as fossil fuels, 7, 55, 77, 127–36, 140–42, 150, 181, 187, 190, 194, 198; iron and, 138–42; isotopes and, 149–51; nitrogen and, 149; for plastics, 6–7, 137, 142–49, 152; for rubber, 147–49; telescopes and, 152; in transportation vehicles, 137–40; for writing, 153–56

vacuum tubes, 143
valence electrons, 39–40
van de Kamp, Peter, 121
Velcro, 146
Venus: atmosphere of, 26, 63, 77, 87, 98–100, 183, 218; carbon and, 5, 17, 39, 63, 77, 99, 183; climate issues and, 184, 185; Copernicus and, 53; life and, 77, 87, 97–101; temperature of, 87; water and, 98–99
Victoria, Queen, 171
Viking spacecraft, 102–3
Virgo, *206*
volcanoes: carbon dioxide and, 87, 167, 185; climate issues and, 70, 87, 99, 186, 192–93; diamonds and, 158, 167–69; Io and, 61; pipes and, 158–59, 167–69; polycyclic aromatic hydrocarbons (PAHs) and, 48

Wallerstein, George, 221n5
Ward, Peter, 81–82
War of the Worlds (Wells), 1–2
water: calcium carbide and, 136; carbon-silicate cycle and, 185–88; chemistry and, 35, *41*; climate issues and, 186, 194–99; diamonds and, 165–67; flooding by, 158; and glaciers, 88, 131, 188–95; habitable zone (HZ)

water (*continued*)
and, 94–96; India ink and, 154; Lavoisier and, 13; life and, 70–71, 75, 77, 82–94, 98–104; Milky Way and, 122, 124; planet formation and, 57–65; plastics and, 7, 143; pure, 146, 156; seawater, 156; silicates and, 65, 165; as solvent, 93–94; storage of, 7; temperature and, 146; vapor, 75, 98, 100, 122, 184, 195–96; Venus and, 98–99
wavelengths: Doppler shift, 122, 124, 204–9, 212–13; light and, 29, 46, 107–10, 113–16, 156, 176, 182, 205–7, 212, 221n4, 223n1; and redshifting, 204–9, 212–13
weather, 4, 194
weathering, 30, 93, 186–87, 193
Welles, Orson, 102
Wells, H. G., 1–2
white dwarfs, 11, 28, 37, 121, 170, 215–16
Wickramasinghe, Chandra, 73
wind farms, 134
Wollaston, William, 29
writing, 153–56

Xerox machines, 153
X-rays, 72, 109–11, 171