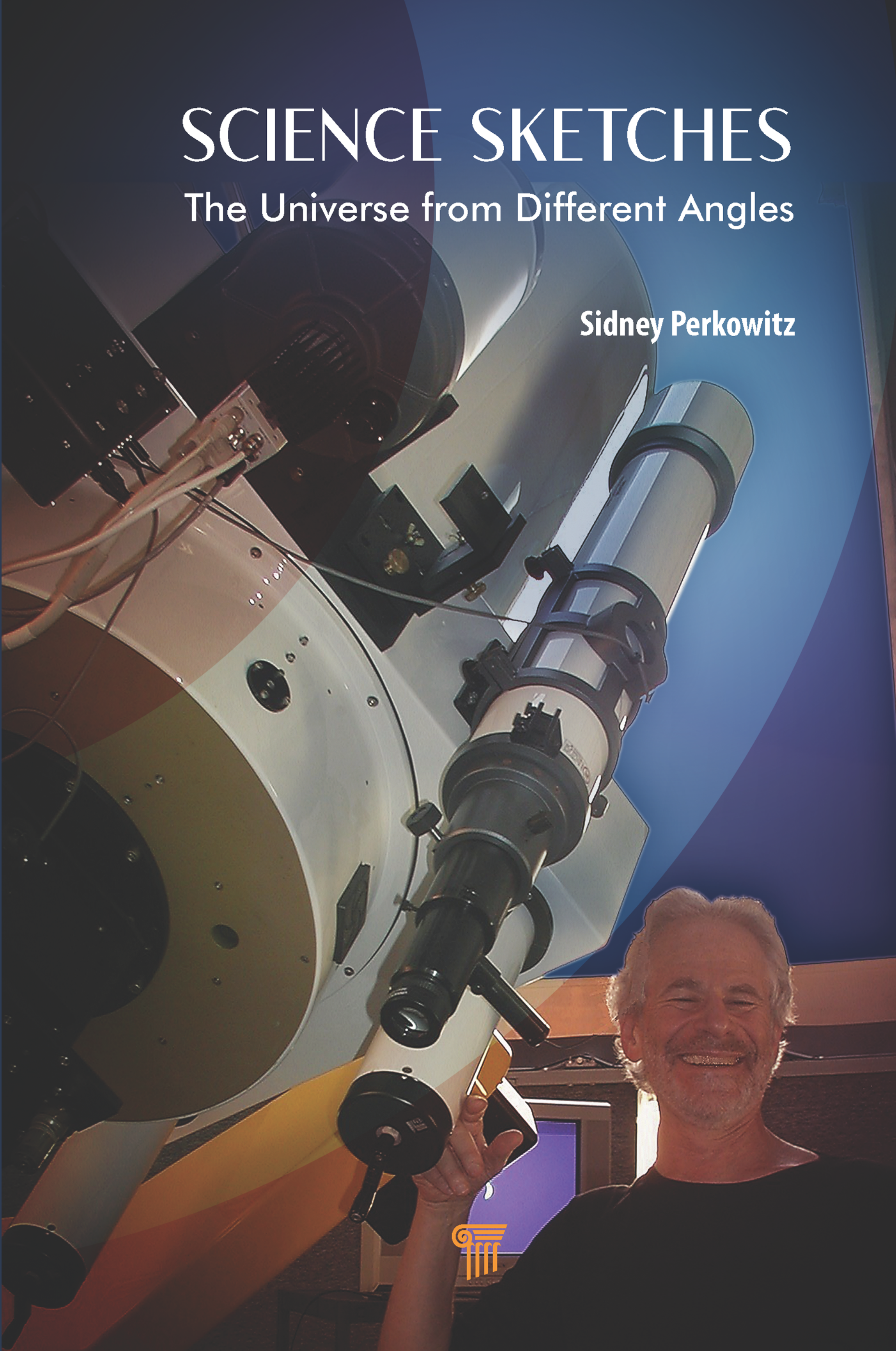
SCIENCE SKETCHES

The Universe from Different Angles

Sidney Perkowitz



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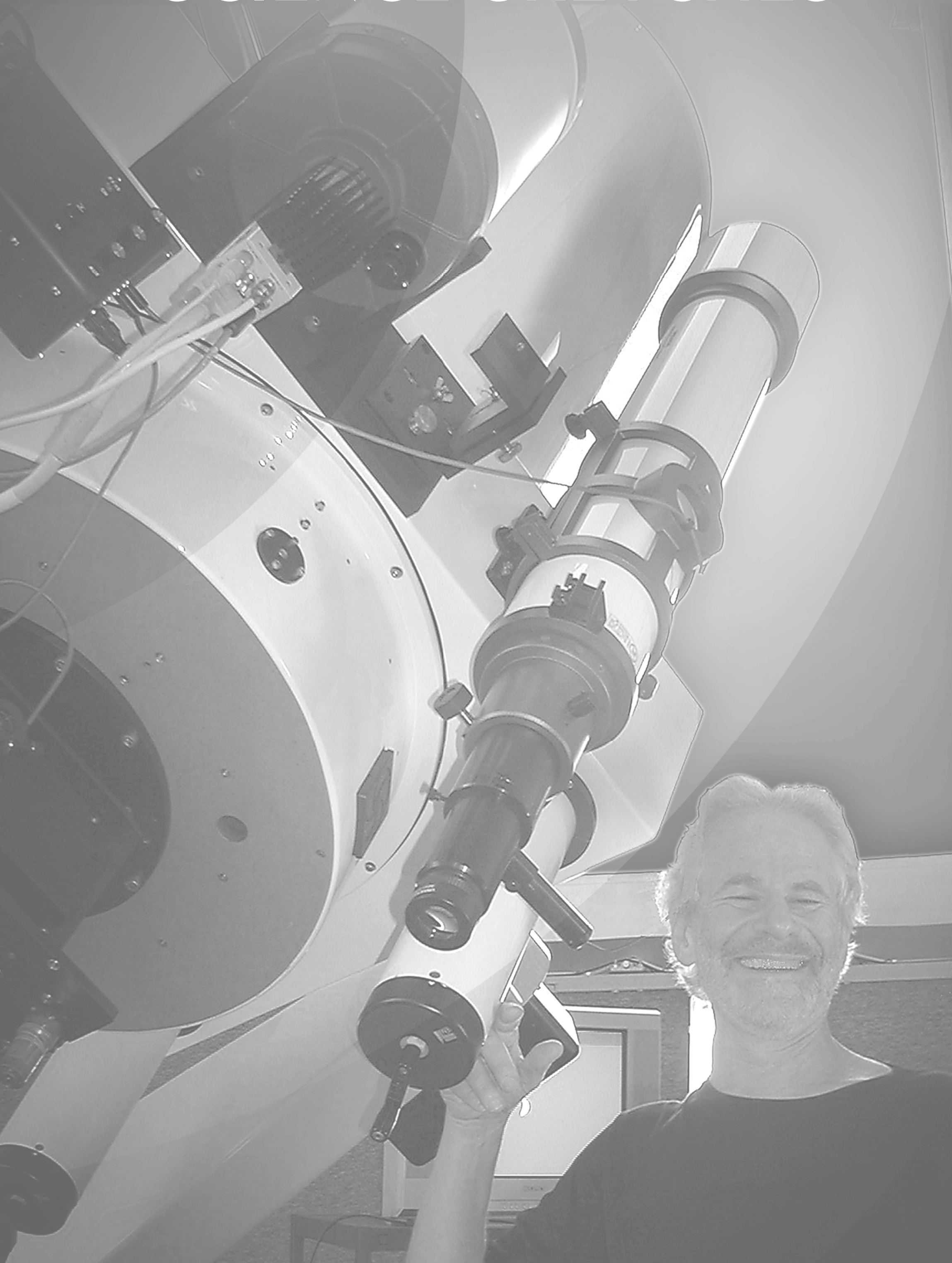

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Science Sketches: The Universe from Different Angles

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To my beloved wife Sandy and my wonderful family,
Mike, Erica, and Nora—I'm grateful that you're here.

Contents

*Article written for this book.

Preface: The Universe from Different Angles

This book is the second collection of my published articles and essays. It follows the 50 articles in *Real Scientists Don't Wear Ties* (Jenny Stanford Publishing, 2019) with 52 more pieces. They appear in formats from quick reads to deep dives, and cover topics from quantum gravity to science in the media, from neuroscience to technology in society. This new collection contains mostly items from the last decade right up to this year, but you'll also find older pieces from as far back as the 1990s (for some of these articles where an update to a fact or event would be helpful or interesting, I have provided that in a brief note).

I selected the entries with an eye toward variety in chronology as well as coverage. The topics range broadly in time from the historical and enduring to the latest science and technology and their current effects. Except for two pieces I wrote specifically for this book (see Contents), what I present here comes from varied print and online sources with different goals and styles; all the articles, however, have been written for general readers. Their lengths cover a range, too, from 600 words to over 3000, and these are distributed throughout the book. One difference from *Real Scientists Don't Wear Ties* is that I sometimes place pieces about science in the media alongside articles that directly treat science and technology, as a way to broaden and enliven the discussion.

In *Real Scientists* I related how I became both scientist and writer with a career in physics research and teaching, followed by a second career in writing that draws on my scientific training. I won't repeat that history, except to say again that I have been fortunate in combining two personal passions into one satisfying whole. This became especially clear during the time when the COVID-19 pandemic brought our society to the point of lockdown. For myself, I'm thankful that I have been able to continue writing under these conditions. This kept my mind and attention engaged and contributed to my mental health during these difficult times.

I had structured the 50 pieces in *Real Scientists* by organizing them into three main categories: science, meaning discussions about pure science and its theories and ideas; technology, meaning pieces about science applied to daily life, medicine, space travel, and more; and culture, specifically, the interactions of science with the arts and the media, and the practices of scientists that define a scientific culture.

The new articles in *Science Sketches* represent the same general threads, but here they appear under different aspects of what each thread means. One influence came from another book I wrote in the same time frame as *Real Scientists*. In researching *Physics: A Very Short Introduction* (Oxford University Press, 2019), I was reminded that the word "physics" comes from a Greek root that means "nature." At its most fundamental, science is the study of nature. Along with art and religion, it is one way that humanity tries to make sense of the natural world and the universe that surround us. Thus one major heading in this book is "Looking at Nature Without and Within," an appreciation of how we have found ways to peer deeply into nature, and also of how much is left to be examined and understood.

Another influence has been my deepening understanding of the role of technology and applied science in our society in areas such as biomedicine, algorithmic decision making, and artificial intelligence (AI). Recent dramatic, society-changing events such as the successful development of COVID-19 vaccines, the growing realization of how police treat people of color in the United States, the daily impact of social media and surveillance, and our increasing appreciation of the lack of equity between women and men in science and elsewhere—all these give new weight to the power of technology to change our lives for the better, or for the worse. What I've read, seen, and encountered about these issues has extended my thinking and my writing about technology and its ethical uses. This resulted in many of the pieces, especially recent ones, that I chose to appear here under the heading "Technology in Society."

Some of this coverage also appears under "Science, Fiction, and Art," because of how the pandemic affected my writing and film viewing. COVID-19 directly inspired the pieces under "Imagining the Pandemic." The disease also redirected my writing about science in films, which had focused on Hollywood's science fiction extravaganzas. When the pandemic emptied movie theaters, the production and distribution of major feature films halted or diminished (with long-term results yet to be seen). Like many, I turned to my computer to watch films, including number of documentaries and stories from independent filmmakers. Many of these brilliantly illuminate how science and tech affect individuals and society. Most of my comments about independent films appear under "Science, Fiction, and Art," along with articles about feature-length science fiction films that represent science and scientists well, or say something important.

This book presents different ways for you, the reader, to engage with science and technology. You can dip into the list anywhere to choose a short appetizer or a long entrée. For many of the articles, you can read further in the set of references I provide. But the whole menu is here for you to enjoy. I hope you will.

Sidney Perkowitz

Atlanta, GA, and Seattle, WA, USA
2020–2021

Acknowledgment

I’m happy to acknowledge the efforts of Jenny Rompas and Stanford Chong of Pan Stanford Publishing, who initially approached me about the possibility of writing a book for them. They liked my idea of an anthology of my writing. Jenny published my first anthology *Real Scientists Don’t Wear Tie*s under the new imprint Jenny Stanford Publishing, and she and her staff proved a pleasure to work with. After that good experience, I’m delighted to continue my interaction with the same group of people to produce this new collection, *Science Sketches*.

List of Illustrations

The illustrations are still images taken from the films listed below, courtesy of the Everett Collection with additional credits as given.

Looking at Nature Without and Within

Introduction

Some scientists work within what we typically call "nature;" botanists and zoologists trek through havens for plant and animal life, and oceanographers study oceans while afloat in them. But nature is bigger and more complex than that, so other scientists do their research at the giant CERN particle accelerator, or the immense telescope in Chile's Atacama Desert, or in their own labs full of exotic equipment. These are tools to study nature, that is to say the universe, in all its parts. We too are part of nature, and so other scientists study humanity individually or in groups using tools appropriate for biomedicine, neuroscience, sociology, and the other human sciences.

Science always seeks to look more deeply than our eyes can see. Our visual apparatus is remarkably acute but what it sees is a mere fraction of what there to sense in the universe, whose natural processes produce radiation extending from gamma rays and X-rays to radio waves. As the pieces below illustrate, these wavelengths can also penetrate and probe nature's small and large scales and where it is opaque.

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The invisible universe

"How to See the Invisible Universe" (2020) discusses how invisible long-wavelength radiation from space allows scientists to examine the early history of the universe, take a close-up view of a black hole, and probe the origins of life. These cosmic wavelengths were accidentally found in 1964 during engineering measurements at Bell Telephone Labs in New Jersey. "Heat Wave" (1991) describes how the great English astronomer William Herschel followed up his observation that certain colors seen through his telescope seemed to carry more heat than others. In 1800, he discovered "heat waves," the invisible infrared cosmic light at wavelengths beyond the red end of the visible spectrum. After describing Herschel's astronomical work, the article goes on to explain the broadly important uses of infrared radiation on Earth.

At the other end of the visible spectrum, "Mood Indigo" (1993) relates how in 1801 Herschel's work inspired the German scientist Johann Ritterto to seek and find invisible short wavelength ultraviolet light beyond violet light; and how in 1895 Wilhelm Roentgen accidentally discovered X-rays at even shorter wavelengths that gave them great penetrating power. These invisible wavelengths enhance medical practice and, when generated at high intensities by gigantic particle accelerators, contribute as well to other areas such as studying molecules and materials.

Black holes, quanta, and gravity

The preceding article "How to See the Invisible Universe" described a scientific effort to photograph black holes. This interest goes deep. Three researchers earned the 2020 Nobel Prize in Physics for expanding the theory of black holes and establishing that a monstrous black hole exists at the center of our own galaxy. "A Supermassive Lens on the Constants of Nature" (2020) describes the research that produced this Nobel award and also shows that the galactic black hole provides a novel tool to study a particular constant of nature that defines the universe and perhaps the fact that life exists as it does. Black holes equally fascinate the general public as I've seen in my own outreach activities and as confirmed by the data I discuss in "The Most Popular Physics Meme Ever" (2015).

One reason that physicists are interested in black holes is that work by Stephen Hawking suggests that their behavior gives clues to how to merge the two great theories of physics, quantum mechanics and general relativity. But unifying these theories has been an elusive goal. "Can Space Experiments Solve the Puzzle of Quantum Gravity?" (2020) explains why this is difficult, and describes new experiments in space that may give answers. The difficulty is partly due to the fact that over a century after Max Planck introduced the quantum theory, we still hardly understand it. That puzzlement is described in "Small Wonders" (1993). Today full understanding of the quantum still eludes us but "The Quantum Random Number Generator" (2019) shows that researchers have learned to use its peculiar properties in unique real-world applications.

Observing our Earth

The previous sections covered nature at its biggest and smallest scales. Here I consider the intermediate scale, which is what the word "nature" is usually taken to mean; that is, our own planet, its phenomena, and the life upon it.

"Sunlight, Life, and Time" (2018) addresses our Sun, the Earth's essential natural energy source. The piece describes four films from independent filmmakers about the violent solar activity that produces solar radiation and its effects on Earth, from beneficial photosynthesis to harm from ultraviolet light. The solar energy reaching us is critical in setting the Earth's temperature and the onset of global warming. One of the films also makes the point that whatever happens on the Sun, we know about it only 8 minutes later because of the finite speed of light.

"Flash!" (2019) is a scientific and cultural history of violent natural activity in our atmosphere, the phenomenon of lightning. Carrying meaning in ancient mythology and religion, a lightning bolt also carries tremendous power. This destructive capability is increasingly important as the effects of global warming make lightning strikes more prevalent around the world, but there is also the possibility of extracting useful power from lightning.

“We and the Earth Breathe Together”(2019) considers 10 science-based independent films that tackle climate change and the atmospheric pollution that encourages it. Some of the films paint a dystopic future where the atmosphere is so toxic that people must wear breathing apparatus or buy oxygen, but others hold out hope and give evidence that we may be able to turn back these effects. I treat climate change again later in the pieces “If Only 19th-Century America Had Listened to a Woman Scientist” and “Science Advances and Science Fiction Keeps Up.”

Peering inside the body and the mind

In 1895 Wilhelm Roentgen’s discovery of X-rays gave science and medicine the power to look inside the human body without cutting into it. “The Better to See You With” (2019) explains how it and other techniques, such as ultrasound and magnetic resonance imaging (MRI), were developed to give an array of tools to examine the body and the brain. Since the piece was written, there has been progress that allows MRI to be used diagnostically even on some people with implanted heart pacemakers and defibrillators, which was not initially possible.

One form of MRI, functional MRI (fMRI), makes it possible to examine the brain’s neural processes as it forms thoughts; that is, to study the mind. One brain–mind interaction probed by fMRI is synesthesia, the mixed sensory response such as seeing images when hearing sounds that some people experience. “The Power of Crossed Brain Wires” (2020) gives the history and science of synesthesia, illustrated by my personal involvement with it. The piece also shows how synesthesia may give clues to an enduring mystery of neuroscience, how physical brain activity produces our own sense of self-consciousness.

We also know that the brain’s neural connections are electrical in nature. “Can Zapping Your Brain Really Make You Smarter?” (2019) gives a brief history of how this knowledge has grown since the early Greeks, and how it is used today in transcranial direct current stimulation (tDCS) in which a small electrical current is applied to the brain. Some research shows neural benefits from tDCS, but scientists warn that performing tDCS at home with unregulated consumer devices may be unsafe.

How to See the Invisible Universe

In 1609, the great Renaissance scientist Galileo Galilei put a handheld telescope to his eye and looked to the heavens. In doing so, he opened the universe to direct human vision. Today, it remains a thrill to see Saturn's majestic rings through an optical telescope, as Galileo did. Astronomers and astrophysicists continue to learn about the universe, examining galaxies, stars, and planets at the visible light wavelengths.

Astrophysicists also study the invisible universe: at electromagnetic wavelengths, shorter than visible light; in the gamma ray and ultraviolet regions; and at even longer wavelengths, in the infrared. Each range gives new information. But it was a surprise when we found how much more information there is at still longer wavelengths, millimeters to centimeters. We generate such waves within microwave ovens and automotive cruise control systems. These waves also occur naturally in space, where they carry clues about the birth and growth of the universe, the centers of black holes, and the origins of life itself.

It's a truism in science that important discoveries often arose from serendipitous events. The German physicist Wilhelm Roentgen discovered X-rays after he saw an unexpected glow from a fluorescent screen in his lab. The French physicist Henri Becquerel discovered radioactivity when he noticed that photographic film stored in a drawer had become unaccountably fogged. Roentgen and Becquerel won Nobel Prizes in Physics for their discoveries. These researchers displayed the observational skills and the curiosity that lie at the heart of science, bringing us to a deeper understanding of nature.

Likewise, observations of the invisible universe, detected by means of long-wavelength photons in space, were first found by accident, in 1964. In a project to develop orbiting communications satellites, researchers Arno Penzias and Robert Wilson, at Bell Telephone's New Jersey laboratories, used a ground-based antenna pointed at the sky. Unexpectedly, it picked up a signal of unknown origin at a wavelength of 7.35 cm, which remained constant no matter where in the skies the antenna pointed.

To study this radiation without interference from the Earth's atmosphere, in 1989, NASA launched the Cosmic Background

Explorer (COBE) satellite into space, equipped with instruments to measure the strength and wavelength of millimeter and centimeter waves. The results, published in 1993, showed a distinctive peak at 1.07 mm, a "blackbody curve," which describes the electromagnetic waves emitted by any object above absolute zero temperature. The peak intensity and wavelength depend on the object's temperature. Our Sun, a hot body at 5,800 Kelvin (K), emits visible light with a peak at 500 nm. The COBE data perfectly followed the same theory but calculated for the extremely low temperature of 2.725 K, which generates millimeter and centimeter waves.

The COBE measurement of the so-called cosmic microwave background (CMB), along with the fact that the universe is expanding, provides strong evidence for the Big Bang. According to the theory, the universe began 13.8 billion years ago at an unimaginable density and a temperature of billions of degrees. The Big Bang produced highly energetic short wavelength photons that survive today as relics of cosmic birth, although they have changed: as the universe cooled and expanded, the photons carried lower energies at longer wavelengths. Today, they fill a universe whose temperature is near absolute zero. The clincher is that the measured value, 2.725 K, agrees with the theoretical prediction of 3 K based on the Big Bang—a prediction made in 1965, shortly after Penzias and Wilson made their accidental discovery.

The COBE results showed something else that ground-based data had not: the CMB—and therefore the temperature—was not perfectly even but varied slightly across the sky. This was important news about the state of the universe at the time when photons began traveling through it, 400,000 years after its birth. The temperature fluctuations track changes in the density of the hydrogen that then filled the universe. These density variations are the seeds that grew into today's cosmic macrostructure, consisting of strings of galaxies surrounding huge empty voids.

Mapping the Big Bang

To closely examine the density variations, in 2009, the European Space Agency (ESA) launched its Planck spacecraft, named after Max Planck, who derived blackbody theory in 1900. With improved technology (compared to COBE), the Planck spacecraft scanned the skies at nine wavelengths between 0.35 mm and 1 cm, measuring temperature differences down to 1 μK. After the spacecraft gathered the data, ESA scientists turned it into a high-resolution map of temperatures in the early universe as they appear in the CMB.

Scientists analyzed that map with the Big Bang theory and general relativity (Einstein's theory of gravitation) in mind. The goal was to see how the density variation produced a universe that contains all of the following:

- ordinary matter, the kind that surrounds us on Earth;
- dark matter, which exists in space and has gravitational effects but cannot be seen;
- and dark energy, which seems to fill all space and acts to expand the universe against gravity.

The final results, announced in 2018, give the most precise and complete description of the universe to date. We now know that it is approximately 13.8 billion years old, and is made of 4.9% normal matter, 26.6% dark matter, and 68.5% dark energy. To underline the point: 95.1% of the cosmos consists of entities unlike anything on Earth, whose nature we do not fully understand—we can only speculate until we learn more.

The analysis of the Planck data provided another surprise in the value it gave for a particular number, the Hubble constant, H_0. In 1929, the American astronomer Edwin Hubble, observing galaxies through what was then the world's biggest optical telescope, at Mt. Wilson, California, confirmed earlier ideas that the universe is expanding. Hubble derived a value for H_0, which gives the rate of expansion at different distances from the Earth or any other specific spot in space. H_0 has since been recalculated from newer astronomical data, but the value from the Planck data was 8% smaller than the recalculated value, indicating a slower expansion rate in the young universe. That discrepancy is now under intensive scrutiny, although we may have to wait until a planned new space mission, to take place in the mid-2020s, helps us to learn if it is due to an error or represents new knowledge.

Taking a picture of a black hole

Observations at millimeter wavelengths also made possible the first image of the most exotic cosmic object we know, a black hole. These regions, where incredibly dense matter produces a gravitational field so strong that not even light can escape, were predicted from general relativity. Since then, they have been observed in our own galaxy and elsewhere—not directly, but by means of gas molecules and dust particles pulled in by the powerful gravity. These components collide and generate tremendous heat, X-rays, and gamma rays, creating a glowing accretion disk around the hole.

In 2009, the Event Horizon Telescope (EHT) research consortium set out to image a black hole at the center of a distant galaxy denoted as M87. An event horizon is the imaginary surface around a black hole that represents the "point of no return;" once past it, no incoming object or photon can leave. But measurements had shown that photons of about 1 mm wavelength could escape the intense gravity just outside the event horizon and emerge through the accretion disk. EHT planned to detect these photons and turn them into a picture.

This was a tall order, one that required an array of ground-based radio telescope dishes to form an image. At a distance of 55 million light years, the target area within M87 appears as a tiny dot, about the size of a U. S. quarter viewed from 100,000 km away. To obtain an acceptable image, the researchers had to minimize diffraction, where electromagnetic waves are distorted as they enter an aperture, like the bowl of a radio telescope. The bigger the aperture, the less the diffraction. EHT managed the diffraction with a clever scheme that coordinated observations from eight different radio telescope installations around the world. This created an Earth-sized virtual telescope with extremely high resolution.

After recording and analyzing data measured at a wavelength of 1.3 mm, in April 2019, EHT presented its image. The by-now-familiar picture clearly shows a dark "shadow" inside the glowing accretion disk at the center of M87. The shadow closely surrounds the black hole's event horizon, making this the nearest we have come to pinpointing a black hole itself. The data shows that the mass within the black hole is 6.5 billion times that of our Sun. This supports what has been long surmised, that "supermassive" black holes lie at the center of galaxies, where they produce accretion disks called quasars, the brightest known astronomical objects.

Imaging the beginnings of life

Finally, perhaps the most intriguing use of long-wavelength radio astronomy seeks the beginnings of life in an inanimate universe. One theory for these origins is that the necessary complex molecules, such as the amino acids that form proteins, were created by chemical processes in space. These molecules then seeded life by coming to Earth and perhaps other planets. Judging by the life on Earth, the needed compounds are invariably organic molecules, containing carbon, hydrogen, oxygen, and nitrogen. Organic molecules and amino acids have been found in meteorites that reached Earth, which inspires the search for them in space.

A molecule in space is identified by finding features at characteristic "fingerprint" wavelengths in the radiation the molecule emits or absorbs. The organic molecules important for life processes are relatively massive, with ten or more atoms, and typically produce fingerprint features at millimeter to centimeter wavelengths. Radio telescopes operating in this range have found many organic molecules among the more than 200 types discovered in our galaxy and elsewhere, containing up to 13 atoms. A measurement in 2003 reportedly detected an amino acid, but that has not been replicated since. However, "precursor" molecules have been found: molecules that could change into sugars or amino acids with just a few chemical steps.

One telescope system that was used in EHT is also highly effective in seeking organic molecules. In the Atacama Large Millimeter/submillimeter Array (ALMA), 66 dishes working together form the world's biggest single radio telescope installation.

I visited the Atacama Desert, in Chile, years ago and remember a bleak environment—hardly an advertisement for the lushness of earthly life. But Atacama's altitude and dryness are ideal for the ground-based spectroscopic search for the molecules of life. In 2014, researchers using ALMA at 3 mm wavelength found isopropyl cyanide, the first organic molecule discovered in space with carbon atoms arranged like those in the amino acids contained in meteorites. It occurred within a giant cloud of gas and dust in our own galaxy, where new stars form. As the quest for complex, biologically significant molecules continues, researchers should point their telescopes to regions in space where stars and planets are in the process of being born.

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Heat Wave

Sir Frederick William Herschel, the 18th-century English astronomer, was not one to let his curiosity go unsatisfied. His first love had been music, but after a few years of playing oboe in a German military band, he had grown restless. He found a greater challenge in music theory and symphonic composition. Enchanted with the mathematics underlying harmony, he was soon reading texts on pure mathematics. When that subject drew his attention to astronomy, he wrote to his brother: “It is a pity that music is not a hundred times more difficult as a science.” By the time he reached his thirties, Herschel had embarked on an obsessive quest to build progressively larger telescopes while supporting himself as a chapel organist. And in 1781, at the age of forty-three, he discovered the planet Uranus with one of his homemade telescopes and became a celebrated astronomer overnight.

It is little cause for wonder, then, that many years later the same intensely curious mind would make a discovery of an entirely different kind—and arguably of greater significance than the one that brought him fame. It arose out of a subtle anomaly Herschel noticed in his daily study of sunspots. Because he had slightly damaged one of his eyes while observing the Sun, he had begun to experiment with dark glasses of various color. Endowed with what to most people would seem a heightened awareness of the ordinary, he was perplexed when he felt the Sun’s heat more strongly with some colors than with others. So, in 1800 he embarked on an experiment to measure the temperatures of the different colors of light.

He set a prism in a window exposed to direct sunlight, then projected the spectrum of colored light streaming out of the prism onto the top of a table. On the table he placed two thermometers—one resting in the colored light, and the other, an experimental control, outside the projected light beam. And indeed, he found that the temperature registered by the thermometer exposed to the light increased steadily as the thermometer moved from the violet through the blue and the yellow to the red. But he also discovered something much more astounding: when he continued moving the thermometer beyond the red light, the temperature jumped sharply, whereas at the other end of the spectrum, next to the violet light, there was no temperature rise at all. He concluded that there are invisible heat rays residing next to the red.

Herschel had discovered infrared radiation, a vast empire of light that accounts for roughly half the Sun's energy output. If our eyes and minds responded to the immense variety of infrared radiation as they do to visible light, our visual universe would expand in richness, texture, and detail in ways we can only dimly imagine. Sight, of course, is critical to our lives, yet visible light is a small pond in the sea of invisible infrared radiation that surrounds us. More commonly experienced as radiant heat, infrared light is the primary means whereby objects at ordinary temperatures transfer their energy through empty space.

Twentieth-century science has put the infrared spectrum to work in a number of ways. Soldiers find targets in the dark with sensors that "see" in the infrared, as they demonstrated dramatically in the Gulf War. Herschel's own profession, astronomy, has lately been able to peer deeply and continuously into the infrared sky, through satellite instruments and high-altitude telescopes, to gather information about matter too cold and dark to shine in the visible spectrum. Perhaps most significant is that infrared radiation serves as a sensitive internal probe of the workings of complex new materials. For example, it has helped shape the development and fabrication of semiconductor materials, which lie at the heart of all electronic devices. Furthermore, it may be the diagnostic key for understanding how the phenomenon of superconductivity persists at relatively high temperatures in recently discovered families of ceramic-like materials. Infrared radiation could well be the light that guides solid-state physicists to a new wave of superconducting technology.

All the fundamental properties of infrared light follow from the insights of the 19-century Scottish mathematical physicist James Clerk Maxwell. Maxwell wrote down four equations that describe a phenomenon known as an electromagnetic wave, which always propagates at the speed of light, 186,000 miles a second. It turns out experimentally that all forms of light, including the visible and the infrared, are electromagnetic waves.

The most vivid image for understanding the nature of electromagnetic waves was devised by the 19-century English physicist and chemist Michael Faraday. Imagine positive and negative charges at rest at various points in space. Just as one feels the effects of static electricity on a dry winter day, the charges "feel" attraction toward or repulsion from one another across space. Faraday made the interaction visible by drawing lines along the direction of the forces joining the charges. The picture that results, the electric field, is a spidery web of lines of force, each beginning at one charge and ending on another.

It was Faraday's keen wit to grant physical reality to the lines, as if each one were a stretched rubber hand. If one of the charges in the assembly slowly starts to move, the lines joining it to the other charges can stretch or contract, maintaining their smooth shapes. But if a charge sharply changes speed, its connecting bands can accommodate to the change only by developing kinks. And, just like the displacement on a plucked guitar string or the curve in the thong of a cracked whip, each kink travels as a disturbance along the lines of force, finally to jostle the electric charge anchoring the lines at the other end. The original accelerated charge also constitutes an electric current as it moves, which gives rise to magnetic fields with their own lines of force. Hence a magnetic whip cracks as well, to make a magnetic kink along with the electric one. It is worth mentioning that the kinks generally travel much faster than the charges do, just as the disturbance in a taut string can move faster than the finger that plucks the string. In fact, an electromagnetic wave is nothing more or less than a kink in the lines of force, and, as Maxwell showed, it propagates from one charge to another at the speed of light.

Each crack of the whip, or momentary acceleration of the first charge, gives rise to a single electromagnetic disturbance, similar to the single flurry when a stone is dropped into water. But if the originating charge constantly changes velocity by oscillating about a fixed position, a steady train of waves results, the waves radiating outward like concentric ripples in a pond. And like the water waves, electromagnetic waves have a frequency and a wavelength, the distance from the crest of one wave to the crest of the next. Since the waves move at the speed of light, the number of waves that pass a given point in one second, multiplied by the length of each wave, must be equal to a distance of 186,000 miles. Thus, if the wavelengths are substantially shorter than that enormous distance, a great many of them must cross a given point in a second, or in other words the frequency of the wave oscillations must be high. In any event, if you know the wavelength, you can calculate the frequency of the oscillation, and vice versa. The only property that really distinguishes among electromagnetic waves is their wavelength, or equivalently, their frequency.

Infrared light ranges in wavelength from 750 to 1,000,000 nanometers. (A nanometer is a billionth of a meter.) The range is further subdivided into the near (750 to about 10,000 nanometers), the mid (10,000 to 50,000 nanometers), and the far. Beyond that lie even longer waves—millimeter waves and microwaves. The waves just shorter than the shortest infrared waves are the ones the eye registers as red, and the visible spectrum then continues through progressively shorter wavelengths to the violet, with a wavelength of 400 nanometers.

In fact, the diverse species of light can be thought of as stretched out along a continuous spectrum of wavelengths, similar in concept to the row of keys on a piano. Each key differs in the frequency of the note it sounds, and notes one octave apart differ in frequency by a factor of two, The A above middle C has a frequency of 440 hertz, or 440 waves a second, and the A one octave higher has a frequency of 880 hertz. The wavelengths of visible light thus encompass less than one full octave—only eight white keys on the piano—whereas the invisible infrared world discovered by Herschel covers more than ten octaves—an entire keyboard full of light, and then some.

This picture makes it possible to understand why radiation at infrared wavelengths is so bound up with our everyday lives. Any matter at a temperature above absolute zero radiates electromagnetic waves to one degree or another simply because the atoms within the matter vibrate. Vibrating atoms are the manifestation of temperature; as the temperature rises, they vibrate faster. Because each atom has an overall electric charge that oscillates along with it, the atoms generate electromagnetic waves at the frequency of their oscillations. At the temperatures encountered in ordinary experience, the frequencies of the waves generated by the random, thermal oscillations of atoms lie in the infrared, and mainly in the near and mid ranges.

Thus, every ordinary object—a tree, the human body, a military tank—acts as a miniature sun, giving off radiant heat to its surroundings. Detecting those emissions can give night vision to a gunner or enable an earth-orbiting satellite to make the