SCIENCE

clear descriptions of genetic technology, thrilling details of space sci-
, and riveting descriptions of how curiosity-driven science has led to
cures for pain and potential cures for cancer, James shows the irreplace-
value of pure research. Her expert knowledge, personal experience, and
phorical felicity provide a rare and spirited defense of pure science with
ailed historical map of the byways from pink Yellowstone slime to ge-
fingerprinting, from twitching frog legs to the first battery, and from
sightings of black hole evaporation to WiFi. The benefits of these kinds
plorations could never be predicted beforehand. They are the results of
cience—adults at play, trying to find out about the real world."

DORION SAGAN, author of *Cosmic Apprentice: Dispatches from the Edges of Science*

ce has surprised humans with incredible insights and great strides in
uality of life for centuries. Renée James's book walks you through the
ing relationship between scientific research and producing a better
around us—it's an inspiring, eye-opening journey."

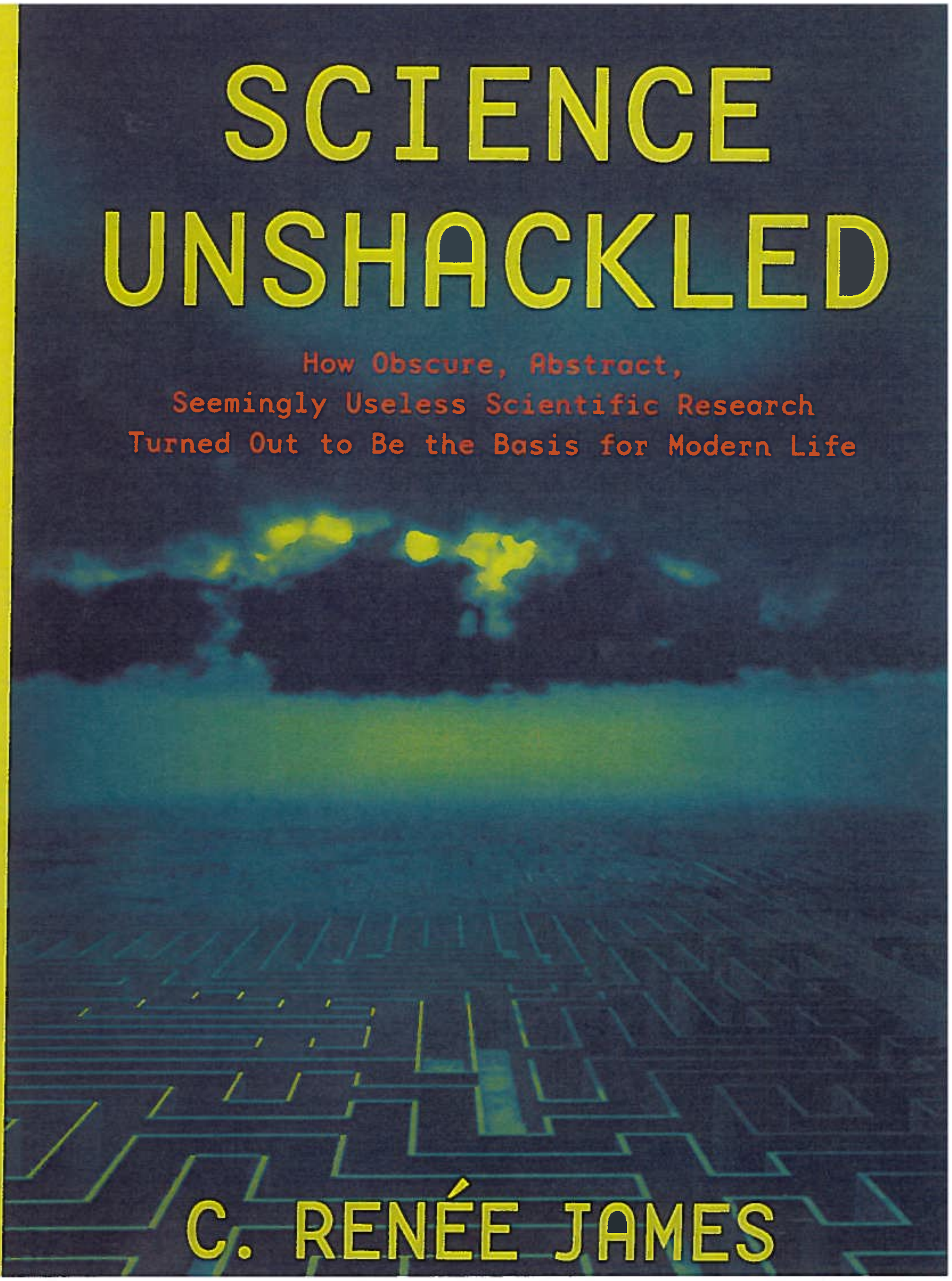
DAVID J. EICHER, Editor-in-Chief, *Astronomy magazine*

ce *Unshackled* is entertaining, informative, and thought-provoking—the
I read this well-written book, the more I liked it. Renée James weaves
her a narrative that breathes new life into the idea that basic research
ad to the development of practical technologies, even though we can't
s predict the tangible benefits. She also does a good job of explaining
plex scientific ideas without dumbing them down. Both experts and
al-interest readers will find this book appealing."

JOHN M. HENSHAW, author of *A Tour of the Senses: How Your Brain Interprets the World*

JOHNS HOPKINS
Baltimore | www.press.jhu.edu
ISBN 13 978-1-4214-1500-0

James SCIENCE UNSHACKLED



SCIENCE UNSHACKLED

How Obscure, Abstract, Seemingly Useless Scientific Research Turned Out to Be the Basis for Modern Life

C. RENÉE JAMES

Fall 2014

SCIENCE UNSHACKLED

Sultana —
Thank you for all of
your help!
—Renee

PART V

*** Dreaming of the Star Treatment

IMAGINE. You finally have some free time and you think you'll catch up on some reading. Your friends have recommended Rebecca Skloot's *The Immortal Life of Henrietta Lacks*, so you crack it open one lazy afternoon. It seems like a great choice, something that digs deep into the issues of social strata, medical ethics, and racism both before and after the civil rights movement. Good food for thought. But as you read, the personal story of Henrietta Lacks begins to hit you. In what seemed a medieval form of torture, the treatment for cervical cancer in 1951 was literally to sew radium inserts inside the 30-year-old Lacks, with the hopes that the radiation from them would kill the aggressive cancer before killing the patient. The side effects were incomprehensible. The region near the radium inserts became cooked with radiation, causing searing pain. The skin of her abdomen was blackened from the treatment. She was weakened and nauseated, all while trying to take care of five children, one born just months before the cancer diagnosis. You read with horror of her ignoble death and the unmarked grave of a young cancer victim who, even in death, suffered indignities that would have legal and ethical ramifications in the twenty-first century. Surely things have changed since then, you think, recalling a colleague's months-long absence during her own battle with cancer. Surely in this age of smartphones and smart bombs we have progressed past the scorched earth strategy for cancer treatment. Haven't we? You take a quick glance at the National Cancer Institute's website only to find that, while many things have improved in the intervening decades, some cancer treatments still seem barbaric and outdated. You feel a wave of anger, sadness, and helplessness, and you wonder if perhaps it's time for the nation to divert some of its monetary and intellectual resources from the impractical and pointless studies about impossibly distant objects to the problems we face right here. After all, it seems ridiculously far-fetched to think that funding attempts to understand the precise inner workings of our nearby star or the chaotic surroundings of unimaginable objects could ever be of any practical use to someone you know with cancer. It doesn't dawn on you that stars are our cousins, our atoms forged together in the same furnaces, and that by understanding them, we can understand ourselves.

30 INGREDIENTS OF THE STARS

In 1806, Jane Taylor, a somewhat obscure English poet, penned the most famous astronomical opus of all time. Perhaps you are familiar with it. If not, it's a safe bet that every child in your neighborhood is. Let me refresh your memory:

Twinkle, twinkle little star
How I wonder what you are.

Perhaps it was 30 years of hearing this song that drove French sociologist Auguste Comte to declare of stars, "We understand the possibility of determining their shapes, their distances, their sizes and motions, whereas never, by any means, will we be able to study their chemical composition." This was a particularly interesting statement for a nonscientist to make, especially considering that in 1835 the universe had already begun dropping subtle hints that a star's light might reveal telling information about the nature of the star.

Extracting information from starlight required dissecting it first, separating the colors by means of a prism. Only then could one even begin to divine the fundamental workings of the stars. In 1802, just a few years before the first publication of Taylor's immortal poem, William Hyde Wollaston reported his attempts to improve the dispersion of prisms so that they could spread the sunlight out into ever wider rainbows. Amid the laundry list of transparent substances that he had run sunshine through, he announced something odd. The continuous rainbow wasn't. Instead of an unbroken band of light, the sun's spectrum was cut into pieces by strange dark lines.

Wollaston naïvely suggested that these lines were, perhaps, the true dividing lines for the colors.

Prisms improved and scientists took note. By 1817, Joseph Fraunhofer had painstakingly catalogued dozens of these dark lines in the spectrum of the Sun and, for the first time, in the rainbows of the stars. His alphabetical labeling system for the most prominent lines is still in use. For instance, there are the D lines, two dark stripes in the orange-yellow region of the rainbow. Were you to hold up a DVD or CD at an angle to a low-pressure sodium street lamp, you would see not a rainbow but a distinct orange-yellow blob. And if you could measure the wavelength, you'd find that it fell at the same place as Fraunhofer's D lines. In 1817, though, nobody had any clue that sodium atoms have a special relationship with those particular colors.

Fraunhofer was also tantalized by the observation that *some* of the dark lines in the rainbows of *some* stars matched those in the Sun, but others did not. The strengths of some lines even depended on the time of day and the time of year, leading early spectral explorers (or spectroscopists) to the appropriate conclusion that some component of Earth's atmosphere was filtering out those colors. But the logical deduction that the other, unchanging lines must represent something in the makeup of the Sun and the stars had to wait half a century for the work of Gustav Kirchhoff and Robert Bunsen.

You have most likely heard of Bunsen, or at the least had experience with the gas burner that bears his name, despite the fact that he didn't invent it. Bunsen did, however, make a number of game-changing contributions to chemistry and geology for which he is scarcely remembered. Like most chemistry students, Bunsen was a fan of incinerating various substances in what is now known as a Bunsen burner. He was particularly surprised by the "splendid light"—a brilliant white light reminiscent of a welding torch—produced when a magnesium strip was inserted into the high-temperature flame. Spurred by a now obsessive drive to understand the light produced by burning various substances, Bunsen then found himself working with Kirchoff, who had "made a wonderful, entirely unexpected discovery in finding the cause of the dark lines in the solar spectrum . . . thus a means has been found to determine the composition of the Sun and fixed stars."

Perhaps it was a good thing that Comte died before Kirchoff and Bunsen got together to publish their findings. Now collectively known as Kirchoff's Laws of Spectroscopy (again Bunsen's contribution is ignored), they were the rules that the universe followed when creating light. The Sun's rainbow, including the dark lines cutting it up, was the natural result of running light from its hot, dense inner portion through the cooler, lower-density outer layers. The dark lines, far from being dividing lines for the colors, instead betrayed the identities of the various atoms making up that outer layer. In other words, the elements in the atmospheres of the Sun and stars were acting as filters, picking off the very same colors that they produced when Bunsen incinerated them. This meant that each element had its own spectral fingerprint, a set of wavelengths that it could either emit or absorb depending on the conditions.

Comte's certainty was shattered by equipment available to any modern high-school chemistry student. Light, even that from distant stars, could be unraveled and analyzed by the relatively simple spectroscope—a combination telescope, prism, and wavelength calibrator. Four decades after the work of Kirchhoff and Bunsen, Charles A. Young of Princeton University hailed the spectroscope as "a new and powerful instrument of astronomical research, resolving at a glance many problems which before had seemed to be absolutely inaccessible to investigation." Young even dared to suggest that "its invention has done almost as much for the advancement of astronomy as that of the telescope."

If nothing else, it filled the journals. Once the astronomical applications of spectroscopy came to light, the prestigious *Monthly Notices of the Royal Astronomical Society* frequently ran the equivalent of "how-to" articles in a very slow, decades-long version of a modern-day Internet chat. One letter in the 1864 volume of *MNRAS* even informed spectroscopic observers that an instrument capable of producing useful stellar spectra could be obtained for 66 Bavarian florins. So, it was a Craigslist, too, promoting the pots of gold at the end of the rainbow.

Then in 1880 a series of exceedingly practical articles by P. Smyth on the new field of spectroscopy appeared in the nascent journal *The Observatory*. The lexicon needed cleaning up. Standards needed to be adhered to. After two decades of independent inquiry with essentially homemade instruments, there was solid evidence that the spectroscope was indeed the new telescope. But understanding the Sun and stars would require all spectroscopists to be, well, on the same wavelength.

Over the next two decades Smyth's vision would be realized. In 1887, Norman Lockyer published *The Chemistry of the Sun*, then the definitive work on the subject, identifying the elements responsible for the Sun's dark-line, or absorption, spectrum. In 1895, Henry Rowland produced the first comprehensive solar atlas stemming from years of work at Johns Hopkins University. During the course of his research, Rowland obtained "the spectrum of every known element, except gallium (of which I have no specimen)." The final list—published in the very first volume of *The Astrophysical Journal*—contained 36 elements. Helium was added shortly afterward, when it was discovered in the spectrum of the Sun's chromosphere, a sizzling hot outer layer of the Sun that approaches 36,000°C (65,000°F) and that can be seen only during a solar eclipse.

31 THE SUN'S SECRET RECIPE

One major problem remained, though. How *much* of each element was present in the Sun and stars? Just knowing that it had calcium, for example, didn't help us know how abundant the element was. The most simplistic approach to getting the exact recipe for the Sun was to note which lines are the darkest. That would, in this naïve understanding, mean there had to be more absorbers picking off those particular wavelengths. More absorbers means darker stripes. Using Rowland's 1895 figures, calcium wins, with iron a close second. Hydrogen came in third place, but this was of little concern because most astronomers were then operating under the assumption that the composition of the Sun would mirror that of Earth. What concerned them was not that hydrogen should rank so low but that common terrestrial elements such as sulfur, nitrogen, and phosphorus did not appear on the list at all.

Others suggested that, instead of looking at the darkness of the stripes, they should simply count the number of spectral lines present. With this method, iron became the most abundant element, followed by nickel. This was a far more pleasing result, as Earth's density indicated a high proportion of these elements, and many out-of-this-world meteorites that had then been discovered contained primarily iron. By this reckoning, hydrogen ranked twenty-second on the list of the 36 known solar constituents. The rare-earth element yttrium ranked higher than the far more common element copper using either approach, and yet it's an element whose existence is completely unknown to the average person.

It was clear that either the interpretation of the spectra or the assumption about the solar composition was incorrect (or both). Although dead, Comte seemed to be constantly reminding the upstart astronomers of his certainty. Maybe we couldn't figure out the actual recipe for the Sun. Maybe we would have to content ourselves with getting the ingredient list.

But all was not lost. In a remarkable feat of foreshadowing, Norman Lockyer had suggested in 1887 that the dark lines tell us not about the actual recipes of the stars but instead about the conditions in the stars themselves:

> Lockyer thinks it more probable that the missing substances are not truly elementary, but are decomposed or dissociated by intense heat, and so cannot exist on the sun, but are replaced by their components. He maintains, in fact, that none of our so-called "elements" are really elementary, but that all are decomposable and are to some extent actually decomposed in the sun and stars.

Perhaps elements *can* be split apart. Perhaps the extreme conditions within stars render certain substances effectively invisible. But J. J. Thomson's discovery of the electron was ten years in the future, and even the most rudimentary understanding of the structure of the atom and the underlying mechanism behind the spectral lines would take yet another decade to materialize. Lockyer, despite being basically correct in his instinct, would never learn the secret recipe for the Sun. He died in 1920, five years before the Sun's main ingredient would be reported apologetically in what astronomy legend Henry Norris Russell judged "the best doctoral thesis I have ever read."

32 READING BETWEEN THE LINES

The author of that doctoral thesis was a woman named Cecilia Payne. Born in 1900, Payne grew up amid a thorough scientific revolution in a household where autographs of naturalist Charles Darwin and geologist Charles Lyell were among the prized family possessions. The classical physics that ruled until the end of the nineteenth century was giving way to a bizarre system that explained the mysteriously constant speed of light, the capricious behavior of the atom, and particles as waves. Geology was beginning to understand that *terra firma* is anything but, and biology was evolving before our eyes. Her undergraduate studies in Cambridge gave her a taste of all these subjects, but physics caught her attention, despite the outright bullying she received from physics giant Ernest Rutherford. His personal attacks, along with a well-timed talk by eminent astronomer Arthur Eddington, who had just led the pivotal expedition to witness the solar eclipse that verified Einstein's bizarre theory of relativity (see part I), ultimately drew her to astronomy instead. She earned her undergraduate degree at Cambridge but was unable to continue graduate studies there. She was, after all, a woman, and it would be another quarter of a century before Cambridge awarded higher degrees to anyone without a Y chromosome.

Luckily for Payne and for astronomy, on the other side of the pond, the Harvard College Observatory had recently set up a fellowship exclusively for female observers. Although Harvard, too, refused to confer advanced degrees on women, those could be taken care of by its sister institution, Radcliffe, a ten-minute walk up the road from Harvard. Payne soon found herself in a new Cambridge, this one in Massachusetts, involved with one of the most active astronomy research groups in the world.

In 1923, the HCO was under the directorship of Harlow Shapley, who had honored Payne's audacious request to work with some of the greatest astronomers of the day. She began work under the stellar classifier Annie Cannon, one of the few women whose names earn a place in introductory textbooks. Payne's intelligence and originality soon set her apart from the field, and she pursued her own research project. It was nothing short of ambitious: she would determine once and for all the exact recipe for the Sun. Just two years later, a day after her twenty-fifth birthday in May 1925, Payne became the first person—male or female—ever to earn a PhD in astronomy for work done at the Harvard College Observatory.

Her dissertation title was a pile of jargon hardly distinguishable from every other technical paper at the time: "Stellar Atmospheres: A Contribution to the Observational Study of High Temperature in the Reversing Layers of Stars." But her explanations within her dissertation were extraordinarily lucid. She spent the first 90 pages laying "The Physical Groundwork." With incredible clarity in writing that is almost extinct in today's dissertations, she artfully solved the problem of the variety of dark stripes in stellar rainbows by appealing not to the recipes themselves but rather to the temperature scales. The makeup of the stars, she found, is actually incredibly uniform. The difference lay mostly in their surface temperatures and hence the energies of light interacting with the elements.

To understand why the temperature makes such a difference, consider the simplest element hydrogen, which consists of a single proton and a single electron and typically no neutrons. Just a decade earlier, Niels Bohr had found that the electron seems to orbit the proton, somewhat in the fashion that a satellite orbits Earth. But just as launching a satellite with too much thrust will send it well outside Earth's gravitational influence, giving an electron too much energy will eject it from the proton's grasp. And, just as giving the satellite a bit more or a bit less energy will force it into a bigger or smaller orbit, giving an electron energy (or taking it away) might force it to be farther from or closer to its proton.

A hydrogen atom is assembled in such a way that light with ultraviolet wavelengths of 91.2 nanometers, equivalent to 91.2 billionths of a meter, or less can rip the electron from its parent proton. (Light is funny that way; the shorter the wavelength, the *greater* the energy.) The highest temperature stars—stars over about 9,700°C (17,500°F)—would be producing so much of this high-energy light that virtually all their hydrogen atoms would be just a frantic plasma of zippy protons and their long lost electrons. Producing the dark stripes that Wollaston first witnessed, however, required the electrons to still be orbiting their protons. From there, they could then absorb certain specific colors (for instance, a particular red wavelength of 656.3 billionths of a meter) only if there were enough atoms with electrons in the right state to pick off that color. That right state, Payne realized, depended on a very fine balance between light with enough energy to get them to their starting point and light with enough energy to get them to their endpoint but not so much energy that it ejected them entirely from the atom. However, the interiors of stars emit a whole rainbow of wavelengths, even many we can't see. For cooler stars, the rainbow is heavy on the lower-energy reds and oranges; for the hottest stars, it's heavy on the higher-energy blues and violets and even ultraviolet. Each atom was a miniature Goldilocks looking for a "just right" balance of energies. That balance could be achieved only with a "just right" temperature, and the "just right" temperature that allowed one element to express itself through absorbing certain wavelengths was different from the "just right" temperature of another element. Thus two objects can have precisely the same chemical makeup but have vastly different dark lines in their rainbows because their light balances—and hence, temperatures—were different.

Of course. It made so much sense. Now that the interaction of light with matter was better understood, the problems of both stellar composition and stellar temperature were elegantly solved. Payne even explained the apparent absence of the common elements oxygen, sulfur, and nitrogen in the Sun. It seems that the spectroscopist's usual range of observed wavelengths did not include the favorite wavelengths of these elements. Oxygen preferred to pick off light in the infrared, a type of light with wavelengths longer than red. Payne optimistically reported that oxygen determinations "should prove accessible in the near future." (Annoyed spectroscopists 90 years later still wrestle with figuring out the exact amount of oxygen in stars.)

It took a century of work and more than a dose of incredible intuition, but the Sun's recipe was finally within our grasp. Even better, everyone could now get back to the happy knowledge that the entire universe—including Earth—was utterly uniform in its makeup.

Or was it? Buried within her eloquent manuscript was a chapter where she discussed the proportions of ingredients in the Sun. It seemed that the simplest atoms—hydrogen and helium—were proving to be troublesomely dominant. But, despite the fact that atomic physicists understood more about the behavior of these two atoms than the rest of the denizens of the periodic chart, Payne cautioned that "the enormous abundance derived for these elements in the stellar atmosphere is almost certainly not real." On top of that, stars seemed positively anemic. Their iron content appeared to be nothing like that of Earth.

But why should she have doubted her results? She had applied the physics masterfully throughout her thesis. The result, even if it made no sense to her or to anyone else, was still the result. Right? Isn't that the way science progresses?

Sadly, even in the sciences, there is often pressure to conform. In Payne's case, the pressure came from scientific giant Henry Norris Russell, a professor at Princeton who was generally accepted to be the authority on all things astronomical. (He later literally wrote the book on astronomy—with two coauthors, that is—that would be the standard for a generation.) She wrote in a letter to a friend that, although she had overcome her personal fear of him, "His power in the astronomical world is another matter, and I shall fear that to my dying day, as the fate of such as I could be sealed by him with a word." After examining her results, Russell wrote a few helpful hints on ways to get the recipes for the Sun and Earth to better agree with each other. Then the hammer fell. "There remains one very much more serious discrepancy," he wrote. "It is clearly impossible that hydrogen should be a million times more abundant than the metals."

A footnote in Payne's dissertation indicates that Russell was in favor of reducing the amount of hydrogen and of raising the bar for iron "by a factor of at least 3 and probably 5—which would put it where it obviously belongs."

"Clearly impossible." "Obviously belongs." Phrases like these are hard to dispute when you are a lowly PhD student, particularly a female one in the early years of the twentieth century. Payne's results had to grow on the scientific community. Frustratingly, it was Russell himself who just four years later would report on the high hydrogen abundance in the Sun. His recipe for the Sun called for one and a quarter cups of hydrogen, a teaspoon of helium, a teaspoon of oxygen, half a teaspoon of "metallic vapors," and a dash of free electrons, mixed well and baked at 10,000°F (recipe may be doubled, tripled, or multiplied by a factor of a billion billion trillion as necessary). In his discussion of the "non-metals," a singularly uninformative term that astronomers use to describe only the two lightest elements, hydrogen and helium, Russell mentions that the fact that visible hydrogen lines show up at all in the Sun is nothing short of a miracle. You see, any electrons that are forced by the right energy light to get into the correct starting level will virtually instantaneously head somewhere else before they get a chance to pick off their favorite colors. Getting enough hydrogen atoms in the right state to filter out what we witness as the dark hydrogen lines is a bit like herding countless tiny negative cats. To get just a few to behave means that you must start out with an insane number of them.

"The obvious explanation," Russell stated casually, "—that hydrogen is far more abundant than the other elements—appears to be the only one." Although Russell made a brief mention of her thesis in his comparison with previous results, that comment was buried 53 pages into a 71-page journal article. The astronomical community assumed the breakthrough was his.

Payne went to her grave in 1979, having claimed for 50 years that the most important thing about Nature is that we continue to make discoveries about it, not that any particular person is given credit. It's not as though her accomplishments went unrecognized. Her career was replete with accolades and honors, including a lifetime achievement award, which was, ironically, the Henry Norris Russell Lectureship. As for her early dread of him while still a graduate student, Payne had her own fearsome reputation. She was known to have a wicked temper lurking behind an often gracious and open demeanor, and she scared at least one student into another field by smashing a collection of glass photographic plates to her office floor in rage. Others reveled in her "delightful chaos." The astronomical community collectively reveres her, though, for so clearly lighting the way to understanding the makeup of the Sun and stars.

33 THROUGH A STAR DARKLY

In the 1920s, the Sun's exact recipe was still very much uncertain, and even Payne and Russell knew that. The values describing the favorite electron hangouts for many atoms were guesses at best, but, as our understanding of inconceivably small objects grew, so did our understanding of colossally large objects that could easily house millions of puny Earths. Spurring progress was the theoretical breakthrough that nuclear fusion—the merging of hydrogen nuclei to create helium nuclei—was the source of the Sun's immense energy, an idea that took hold in the early 1930s. To make the sunshine in which we bask, the Sun destroys four million tons of matter every single second, matter which is converted into energy, as described by Einstein's famous equation $E = mc^2$. That energy then has to work its way through all the layers that are trying to filter some of it out.

Although you can't tell it from here, the type of light created in the Sun's dense, seething furnace would kill us instantly. Every time the protons of once-whole hydrogen atoms are fused together into a helium nucleus in the dense inferno of the Sun's core, gamma rays are produced. Fortunately, the Sun's core is enshrouded by 700,000 kilometers (435,000 miles) of insulation. From the instant it is made to the instant that it finally shines forth in splendor from the solar surface, the energy created in the nuclear reactions endures a random bumper-car ride that lasts anywhere from 17,000 to 100,000 years (some calculations put it as high as one million years; in any event, the sunshine you see today was actually made in the Sun's core sometime in the Pleistocene epoch). During this time, the unimaginably short wavelength gamma rays gradually donate their energy to electrons, protons, and various atoms that have had any number of electrons stripped from them. By the time the energy finally elbows its way to the surface of our star, it is almost exclusively low-energy light, something earthly life-forms can actually make use of.

In this way, the Sun provides us with a sort of physical lesson for our constant tendency to ask "what good is it?" Certainly if we had created a committee to require the Sun to make copious amounts of visible, life-giving energy, the committee would hardly have suggested that the most reasonable first step is to create an incredible amount of something that is fatal to us. But that "useless" energy, especially the way in which it interacts with the two trillion quadrillion tons of material in its way, shapes the conditions for every point in the entire Sun. Only after thousands of years of small steps—many of them backward steps, at that—and complicated interactions, it emerges as the driver of all life on our planet. One wonders whether in a universal budget crunch, the cosmic politicians would look at the Sun as anything but a dynamic whole. If so, would they see the comparatively tiny fusion reactor as a waste of resources that create nothing but a harmful product? It seems ridiculous, yet human society seems all too adept at compartmentalizing its own endeavors while failing to see the power of all the random walks.

At this point, though, the random walk of understanding the Sun's makeup seems a long way from improving anyone's cancer treatment.

34 THE OPACITY PROJECT

It is impossible to imagine exactly how the light and matter dance with and wrestle each other at every layer of the Sun during sunshine's long trek outward. All that energy causes a sizeable fraction of the Sun's interior to churn like a lava lamp as it strains to push out the energy of seven trillion Hiroshima blasts every second. The rest of the time the particles play lacrosse with the light, throwing it from one thing to another. A photon, or piece of light, can manage to go all of about a centimeter at a time before slamming into a new obstacle. Unfortunately for solar astronomers, understanding the precise interactions at every step of the way is crucial to understanding the Sun's exact makeup.

The fact that the Sun is practically next door would seem to make figuring out its exact composition child's play. On top of the Sun's proximity, there also is an entire solar system of objects that formed from the same cloud some 4.6 billion years ago to use for comparison's sake. If meteorites contain, say, two parts cadmium for a million parts silicon, it makes sense that the Sun should, as well. For decades, solar astronomers and meteorite hunters tried in vain to get all of their answers to mesh, but despite advances in every technology available to them, everyone finally had to agree to disagree.

It was, quite honestly, an embarrassment.

In 1984, chagrined by the fact that we still hadn't figured out the composition of our own star, Michael Seaton launched the Opacity Project. Sporting white Isaac Asimov sideburns and a mop of dark hair, Seaton had a talent for understanding not only the complex dances between particles and light but also the even more complex human interactions between scientists.

Seaton was always immensely supportive of his colleagues and students. In 1966, when his graduate student R. J. Harman died tragically in an accident, Seaton told Harman's parents that he would be remembered for his important astronomical work. To this day, one of the fundamental relationships in the study of the remnants of sunlike stars is called the Harman-Seaton sequence. It was this sort of human touch, along with a hard-working, positive attitude, that strengthened countless connections across disciplines. By the time he started the Opacity Project, Seaton had already spent more than three decades attempting to quantify the complicated choreography of atoms, all the while earning the support and admiration of his peers. In fact, just prior to creating his all-star team of physicists, astrophysicists, and programming experts, he was elected president of the British Royal Astronomical Society.

The random walk that started nearly two centuries earlier with an attempt to make an ever-wider rainbow had led to this perfect confluence of personality and technology. Former student and colleague Helen Mason recalls, "The decade of the 1980s was a golden age for atomic physics and spectroscopy. Mike Seaton was in the front row." Seaton would eventually assemble a team of more than 30 astronomers and physicists from France, Germany, the United Kingdom, the United States, and Venezuela. Their charge? Compute how strongly different wavelengths of light interact with different atoms. This yields something called the opacity, or the tendency for the light to be blocked by the atoms. To do this for all the atoms at all the layers of the Sun would require computers with more horsepower than ever. Their first results would take nearly a decade to compile.

It might seem on the face of it like an awful lot of trouble to go through simply to get the Sun's exact recipe. But it wasn't just the Sun's composition that was a problem. The Sun and other stars have a constant flurry of seismic waves traveling through them and across their surfaces. Just as earthly seismic waves help us to divine the inner structure of our planet, these pressure waves in the Sun give us information about the Sun's interior. The interior wasn't shaping up as it should, though, at least not if we understood how the light and atoms in the Sun were behaving. Many answers were distressingly uncertain. The amount of carbon, nitrogen, and oxygen in the Sun had to be adjusted by as much as 45 percent to get models and observations to mesh. This sort of discrepancy threw our understanding of the Sun, along with huge areas of astronomy, into question.

"The practical necessity of solving this problem can hardly be overstated," reads a line in a paper authored by many members of the Opacity Project. Sure, for astrophysicists, but what about the rest of humanity?

35

THE IRON LADY AND THE GOLD STANDARD

You might recall from science class that atoms consist of protons, neutrons, and electrons. The protons and neutrons reside together in the nucleus of an atom, while the electrons circle around them comparatively far away in fixed orbits. A scale model of a hydrogen atom would have a one-proton nucleus several meters wide, and a puny, few-millimeter electron many kilometers away. Hydrogen is simple, though, with only one electron to manipulate. The energies required to shuffle its electron around, or even rip it from its nucleus entirely, are well understood; the closer the electron is to the nucleus, the more energy is required to pull it out of its orbit. The problem of opacity—the amount of light absorption by the material in the Sun—does not arise with the abundant stores of hydrogen that the Sun and stars possess. It arises with the other elements. Something like iron, for instance, has 26 protons and, under circumstances that you've personally encountered, 26 electrons.

The interior of the Sun is unlike anything you've encountered, though, so some atoms will have had one, two, or even thirteen electrons ripped from them depending on where they are in the Sun. An iron atom hanging onto all of its electrons interacts with its own favorite wavelengths of light, whereas an iron atom with only 15 of its electrons interacts with a completely different set of wavelengths.

At Ohio State University, Sultana Nahar has paved the way in computing the specific interactions between light and, in particular, iron. A woman who claims she "never missed a math problem. Never," during her elementary and high school days in Bangladesh, Nahar quickly gained the reputation as the Iron Lady of Mathematical Computations. In 1987, she earned her PhD in atomic physics and soon found herself playing a vital role in Seaton's Opacity Project and its offshoot, the Iron Project. Her mathematical models of the detailed interaction between high-energy light and atoms, aided by the Ohio Supercomputer Center, have helped reduce—but not eliminate—the uncertainties about our own star.

The insides of stars aren't the only places where atoms are subjected to enormous energies, though. Regions around unimaginably dense black holes (see part III) are also flooded with high-energy light. There the atoms make up a violent plasma hurricane as they spiral toward their doom in the black hole. Other cosmic maelstroms include the leftovers from supernova blasts, the catastrophic explosions of stars, and even the dynamic centers of young galaxies. Knowing how the matter and energy theoretically interact in such conditions has helped reconcile observations of these remote, energetic objects. Nahar's computational expertise has reached into the Sun and across the known universe.

By the time Nahar joined the Opacity Project in 1990, her colleague Anil Pradhan at Ohio State University was already a seasoned Seaton veteran. With fellow Opacity Project physicist Yan Yu of Thomas Jefferson University, the three made a formidable team that was awarded hundreds of thousands of dollars in grants from American taxpayers through NASA, the National Science Foundation, and even the U.S. Department of Energy. They explored the interaction of light and matter, digging deep and finding sometimes surprising results.

As scientists had known since the work of Lise Meitner in 1922, the right type of light aimed at an atom can pull one of the atom's inner electrons out. Normally, scientists think of only the outer electrons interacting with light and with each other. When that happens, the other electrons will adjust accordingly. But pulling an inner electron out is kind of like hollowing out the foundation for the other electrons.

What Meitner found out as she explored radioactivity is that electrons, particularly those from the orbit immediately above the hollow, will tend to want to head "inward" to fill that space. But each time an electron falls into an orbit closer to the nucleus, it emits a certain amount of energy in the form of a photon. This photon can then knock one or more other electrons, leaving still more electron vacancies in the process. Other electrons from upper levels will continue to fall to fill the vacancies, each time releasing another photon. Just as removing a block of jewels or candy pieces from the bottom of popular video games causes the other pieces to slide down, sometimes causing unanticipated (and high-scoring) chain reactions, pulling an inner electron from an atom can result in a series of rearrangements and chain reactions of light and matter. Since the innermost electrons are the ones held most tightly to the nucleus, pulling one of those out requires the atom to absorb enormous, but very specific, energies—x-rays or gamma rays—and the subsequent rearranging of the leftover electrons can result in the atom spitting out things you wouldn't normally expect. Ripping out one of the innermost electrons in a gold atom, for instance, can result in the forceful expulsion of many energetic electrons. One parcel of the correct-energy light comes in, but lots of electrons—as many as 20—leave. This property is now known as the Auger effect, named after Pierre Auger (o-zhay, not aw-gher, although the electrons seem to be augering in), who quantified the behavior more precisely in 1923.

Astronomically speaking, this situation explains quite a bit. At certain so-called resonance frequencies, the gold atoms will tend to absorb light energy very efficiently. Far from being an effect that astronomers can simply average over, as they had largely done in the past, it profoundly changed the steps of the light-and-matter dance in extreme environments. When a single packet of light interacting with a heavy element can result in the sudden release of a dozen or more electrons, each of which interacts with light in its own way, even tiny amounts of the heavy elements can make their mark. Such resonances accounted for quite a bit in our understanding of opacity.

And thus the Opacity Project and the Iron Project progressed, incrementally adding to our understanding of interactions on unfathomably small scales and how those interactions affect our observations of phenomena on unfathomably large scales. Yan Yu dropped off Seaton's team in 2003, having devoted two decades of his life to the project, and went to join the ranks of medical physicists. Despite changing fields, Yu kept in close contact with his former colleagues and friends, Pradhan and Nahar. During casual conversation with Yu, Pradhan discussed the discovery of particular resonances of x-rays with heavy atoms. Had he been talking to just another atomic physicist, the exchange might not have gone anywhere. But Yu was now the director of Jefferson Medical College's Division of Medical Physics, an expert on radiation cancer therapies, and someone who could see such a breakthrough from a different angle. The resulting brainstorming session took a turn not to the hearts of atoms or the insides of stars but to people.

Seaton himself died in 2007 at the age of 84, his obituary penned by Pradhan and Nahar, who stated, "There are precious few scientists who have his unique abilities that ranged from profound theoretical insights to mathematical formulations and highly technical computational developments. Mike Seaton was an immense source of inspiration to all who knew him."

36 THERAPY OF THE STARS

If you go to the doctor to get an x-ray, you are voluntarily exposing yourself to a type of high-energy light that can literally pull molecules apart and rip electrons from their parent atoms. The trade-off is fairly clear, though. You will also get the chance to see whether that pain you've been feeling is the result of a fracture or, perhaps, something worse. The typical machine used to image your insides, either a standard x-ray machine or a CT scanner, produces a fairly wide range of energies, all the way from low-energy x-rays that are stopped pretty effectively by your body up to high-energy x-rays that pass through you without interacting strongly with anything. The medium-energy x-rays are often the most useful, interacting with your tissue and bone in such a way that important information can be gleaned from the images.

X-rays are also part of routine cancer therapies. These high-energy types of light damage the DNA inside cells, preventing the cells from dividing. Given that x-rays and other types of radiation are not particular about which types of cellular DNA they destroy, oncologists try to localize the energy around the site of the cancer. In some cases this involves placing a radioactive substance that spits out high-energy light or fast-moving charged particles inside the body itself (as in the case of Henrietta Lacks), while in others, a beam of radiation is aimed at the area containing the cancer. In the former case, the patient is actually radioactive until the substance is removed, forcing the patient to limit contact with others, particularly children. In the latter case, sometimes a daily radiation treatment is required for weeks on end in an attempt to destroy (or at the very least, diminish) the tumor.

It's not difficult to see why this type of treatment can have serious physical and emotional side effects. Radiation aimed at a tumor will kill not just the cancer cells but very likely also the healthy cells nearby. It is not unusual for cancer patients to feel exhausted and nauseated and to suffer great pain. Down the road, the radiation used to kill the cancer might itself be the cause of new cancerous growths.

Despite all of our advances in medicine, our methods for dealing with cancer can sometimes seem strangely barbaric. And since cancer is estimated to affect half the men and a third of the women in the United States at some point in their lives, everyone's life is impacted by it. What could be a higher priority for research funding than curing this insidious disease that will touch us all? Indeed, a 2013 survey indicated that five out of six Americans supported increased funding for cancer research, making it a national health priority. Unfortunately, budget woes resulted in a sequestration that reduced the National Institutes of Health budget by 5 percent in 2013. Although NIH scientists were hopeful that 2014 would see a rebound, funding remained disappointingly flat.

But this is where that two-century hunt for the Sun's recipe can come into play. Nahar, Pradhan, and Yu proposed something called resonant nano-plasma theranostics (RNPT) for a more precise treatment of cancer. They, and ultimately a host of other collaborators, came to realize that if gold or platinum nanoparticles ("nano" indicates the tiniest of workable scales) could be delivered to a tumor, the Auger effect that was discovered to play such a vital role in our understanding of the Sun's opacity and the extreme conditions around black holes could be exploited. The burgeoning field of nanobiotechnology is at work creating what would amount to chemical Velcro that attaches to cancerous tumors. Should these nanoparticles then be subjected to relatively low-energy x-rays tuned to one of those special resonance frequencies, the Auger effect will pull the inner electrons out, resulting in the flood of electrons into the tumor itself.

One of the great advantages of this idea is that those monochromatic x-rays would interact quite strongly with the gold or platinum nanoparticles but much less so with the patient's own tissue. The other advantage is that the energetic electrons released would flood only the sites of the nanoparticles, which have embedded themselves in the cancerous tumor itself. Those energetic electrons would then destroy only the tissue in closest proximity to those particles, namely the tumor. The unlikely band of over a dozen astronomers, physicists, biophysicists, and oncologists estimate that the treatment times and radiation dosages could be cut down by a factor of 10 or 100, certainly a welcome victory for patients currently looking at starting their radiation therapy regimens.

Sad to say, such a specially tuned x-ray device is not as easily obtained as the typical x-ray machine in your local hospital. Only a few such facilities exist in the world, largely in major physics laboratories where medical research applications have only just begun warming up. The RNPT team had an idea of devising a table-top monochromatic source by using the fluorescent properties of atoms, and on paper it is a sound design. However, more work is needed to develop a machine that can generate these x-rays with higher intensity. Furthermore, the required nanoparticles have not been fully developed. For now, the idea of RNPT looks spectacular as a concept, the theory and application fully hashed out by the considerable group of experts, but the practice has been frustrated by funding roadblocks. Feeling the sting of budget cuts, NIH is hesitant to provide support for an as-yet-hypothetical treatment, despite the promise.

Still, the team is forging ahead, with one member spending six months at a European particle accelerator facility to validate the methodology using monochromatic x-rays. Meanwhile, Ohio State University Medical Center's Rolf Barth has added his expertise on platinum compounds used in chemotherapy, as well as laboratory facilities to perform in vitro and in vivo experiments, both of which are practically mandatory for the NIH to be fully persuaded. Preliminary trials on cancerous cells have proven to be promising, and the team is in the process of translating their findings to experiments on live mice. While those experiments have not employed the monochromatic x-rays envisioned, their results are giving the team some hard data for the grant reviewers to consider.

Two decades ago, neither Nahar nor Pradhan would have predicted this career trajectory. Happily immersed in computational physics, it never occurred to Nahar that her work might impact lives in this fashion. She was simply doing what she loved doing, and that was to understand how light and matter affect each other at the most fundamental level. Should this treatment see the light of day, it will owe itself in large part to her curiosity about those minute interactions. In fact, without that basic curiosity, such an idea would never have even made it to the drawing board. "Oncologists *do* have physics backgrounds," she argues. "But they are not involved with detailed research of photon-atom interaction."

Pradhan, ever optimistic about the chances of RNPT to make it through the funding hoops, explains further: "Our work exemplifies fundamental science and the underlying symbiosis between apparently disparate branches of science. This is where new ideas arise."

* * *

Now imagine. In a budgetary spiral, funding is squeezed from NASA, from the NSF, from fundamental research questions in favor of immediately practical applications. RNPT never sees the light of day, nor do dozens of other fruits of the curiosity and symbiosis that define science. Imagine stifling creative connections that could have been made in the labs of scientists who aren't in the business of battling cancer, whose work has no promise of immediate practical benefit. Imagine that your daughter's cancer treatment mirrors that of Henrietta Lacks all those decades ago, all because questions about the stars seemed too remote for the taxpayers to fund.