THE STUFF OF STARS

When a Woman Graduate Student Discovered Abundant Hydrogen in Stellar Spectrums, She Was Bullied into Suppressing Her Results

BY MARCIA BARTUSIAK

THE RESOLVE TO PURSUE SCIENCE WAS NEVER an easy choice for a young girl in the Edwardian age. One could, by dint of talent, drive and the careful choice of one's parents and social class, overcome the more blatant barriers to a scientific education. Cecilia Helena Payne, in her later years as an astronomer at the Harvard Observatory, could point to her mild childhood confrontation with the female stereotype gently enforced by the administration of the church school she attended in London. The female principal told her that she would be prostituting her gifts by embarking on a scientific career. But Payne, born in 1900 in Wendover, England, was descended from a family of scholars and historians, and she eagerly unearthed books on botany, chemistry and physics in the extensive library at her family home. Her father, a barrister, died when she was four, but her mother, an accomplished musician, carefully guided Payne's education. A simple move to a new and more modern school enabled her to immerse herself in scientific studies.

Payne flourished at the new school and became enchanted by the prospect of life as a scientist. "I knew, as I had always known," she confessed much later in her autobiography, *The dyer's hand,* "that I wanted to be a scientist [but] was seized with panic at the thought that everything might be found out before I was old enough to begin!" Of a room set aside for science instruction, she once recalled:

> The chemicals were ranged in bottles round the walls. I used to steal up there by myself . . . and sit conducting a little worship service of my own, adoring the chemical elements. Here were the warp and woof of the world.

Without much ado Payne stayed the scientific course in high school, and in the autumn of 1919, shortly after the First World War ended, she entered Newnham College at the University of Cambridge.

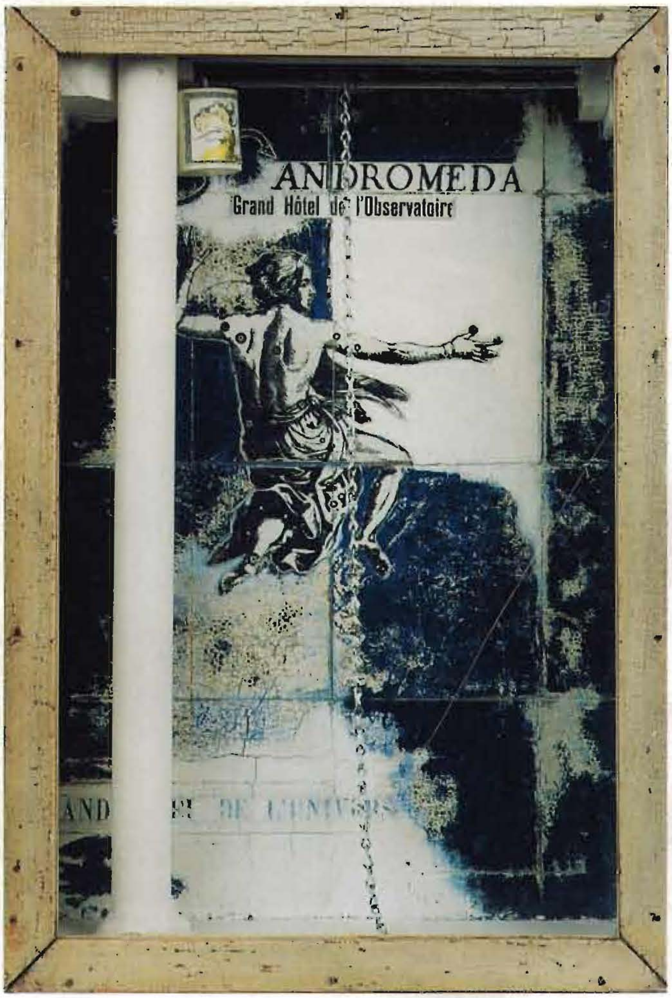
Payne's arrival at Cambridge as an undergraduate coincided with a tremendous upheaval in the understanding of the physical world, when the physics community was reeling from the startling new discoveries thrust upon it. Until the end of the nineteenth century, scholars generally had thought of the universe as a well-oiled clock, and the science of the day was essentially guided by the same principle. The success of Newton's equations of motion had led to a smug assurance that every phenomenon in the cosmos could ultimately be explained mechanically. But nature was not following that script, and things quickly went awry when theorists tried to apply the mechanistic laws of classical physics to the workings of the atom.

For several decades astronomers had been identifying elements in the heavens by comparing their spectral emissions and absorptions with those of glowing gases in the laboratory. The mechanism that gave rise to the light, however, was a complete mystery. Then, in 1913, the Danish physicist Niels Bohr deduced that an atomic spectrum is generated as the electrons in an atom jump from one orbit to another, emitting or absorbing bursts of light along the way. That theory enabled Bohr to calculate the specific colors of light that should be absorbed or emitted by hydrogen, corresponding to the difference in energy between a high electron orbit and a lower one in that atom. Bohr's predictions matched the observed spectrum of hydrogen almost perfectly. On hearing the news, Einstein is said to have remarked, "Then this is one of the greatest discoveries ever made."

Payne had the wit and tenacity to become one of the first astronomers to apply the new laws of atomic physics to astronomical bodies. In the course of her painstaking thesis calculations, which drew heavily on the new physics, she uncovered the first hint that hydrogen, the simplest element, is the most abundant substance in the universe. The reverberations of that plain fact still echo in astronomy. Here is the fuel for a star's persistent burning; here is the gaseous tracer that enables radio astronomers to probe a dark, long-hidden universe; here is the remnant debris from the first few minutes of creation. Payne's discovery did no less than change the face of the material cosmos.

And yet Payne's name (and equally, her married name, Payne-Gaposchkin) is missing from most astronomy books. One can debate the point—for the evidence is not unambiguous—but her failure to gain the very first rank among astronomers seems to have been caused by the forces of sexual inequality. At the last minute, pressured by her more conservative superiors, she virtually retracted her discovery

Remedios Varo, Celestial Pablum, *1958* of stellar hydrogen and published a statement far less definitive than what she actually believed. Her findings were so radical, so different, that she was pushed into softening her thesis. Ironically, the professor who most influenced her to back down eventually confirmed her original suspicions and published the seminal paper on the hydrogen makeup of the stars. Payne has been described as the most eminent woman astronomer of all time. Her doctoral degree was the first ever granted to a student at the Harvard Observatory (the university's physics department had refused to accept a woman candidate). But her failure to achieve recognition for one of the most important advances in astrophysics tells much about the pressures on women scientists as they make their way in a man's world.



Joseph Cornell, Untitled (Grand Hôtel de L'Observatoire), *1954*

AT FIRST IN Cambridge Payne leaned toward a career in botany, a childhood passion. But she made sure to add physics and chemistry to her studies. She found the renowned physicist Ernest Rutherford, who was then conducting some of his most creative experiments at the Cavendish Laboratory, "irresistible." "He was always on the horizon, Payne recalled, "a towering blond giant with a booming voice."

The pivotal decision to dedicate her life's work to astronomy came one winter night in 1919. Four years earlier Einstein had introduced his general theory of relativity, which, among other things, predicted that beams of starlight grazing the sun would get bent by a slight but detectable amount. The bending had been predicted in earlier theories, but in general relativity it was calculated to be twice as large because of the curvature of space-time in the vicinity of the sun. With safe travel restored after the First World War, British astronomers eagerly mounted two expeditions to test Einstein's conjecture. On May 29, 1919, from sites in northern Brazil and on the small island of Príncipe, off the coast of western Africa, the investigators photographed stars near the edge of the sun during a total solar eclipse.

Arthur Eddington, then the foremost astronomer at Cambridge, was a member of the Príncipe brigade, and he presented the results of the fabled undertaking in the Great Hall of Cambridge's Trinity College. The event was sold out, but Payne had miraculously chanced upon a ticket. There Eddington reported that the gravitational deflection of the stellar rays agreed closely with Einstein's calculations.

For Payne it amounted to a religious conversion. She deserted the life sciences and informed the school authorities that she would be devoting her studies to the physical sciences. She was already aware of the problems in her chosen disciplines. Shy and awkward, Payne trembled when she had to sit alone in the front row at Rutherford's lectures, the required seating arrangement for any lone woman in a sea of male students. Her physics lab instructor would often shout at the female students: "Go and take off your corsets!" certain as he was that the steel frameworks of the corsets would disturb his magnetic equipment. But one night, when the Cambridge Observatory was open to the public, Payne encountered Eddington personally. She blurted out, "I should like to be an astronomer." "I can see no insuperable objection," he replied, and he proceeded to widen her opportunities for research.

PAYNE, FACED with the prospect that her only job in England after she completed her degree would be teaching science at a girls' school, was advised to go to the United States. There women had better opportunities in astronomy than they did in England. Another spellbinding lecture, this one given in London by a young sandy-haired Harvard astronomer named Harlow Shapley, prompted Payne to set her sights on Massachusetts, home to the largest storehouse of astronomical data in the world. Her Cambridge professors and colleagues were highly supportive in their recommendations. Leslie J. Comrie, who was by then teaching at Swarthmore College in Pennsylvania, wrote to Shapley that Payne was "the type of person who, given the opportunity, would devote her whole life to astronomy," and that "she would not want to run away after a few years' training to get married." Payne got a fellowship.

Shapley had hoped Payne would work at Harvard on determining stellar brightnesses, a fairly routine endeavor. But Payne was more intrigued by the physical interpretation of stellar spectrums, a more theoretical pursuit and the Harvard specialty. Swift to grasp and apply new ideas, she knew that the work of the young Indian physicist Meghnad Saha could serve as a powerful diagnostic of a star's surface conditions. Saha had recognized that each element stands out vividly in a stellar spectrum only at a particular temperature and pressure, usually when the conditions are intense enough to strip the atoms of some of their outer electrons. Otherwise, the element would remain essentially hidden from view. Saha's ionization theory gave the first physical explanation for the striking distinctions among the various observed kinds of stellar spectrum. In many ways, Saha's realization marks the beginning of modern astrophysics.

Payne was excited by the prospect of verifying Saha's theory with the myriad spectrums available in the Harvard plate collection. She compared her research to an archaeological dig; the data were "bones to be assembled and clothed with the flesh that would present the stars as complete individuals." Her early training in the systematic classification of plants served her well. She looked at hundreds of spectrums (her "celestial flora") and selected certain known lines for inspection. She set up a crude system for estimating the intensities of the spectral features, an arduous task. "There followed months, almost a year I remember, of utter bewilderment," she said. But "nothing seemed impossible in those early days. . . . We were going to understand everything tomorrow."

Gradually, answers did arrive. After days and months of grappling with her treasured plates, the intensities of the lines of silicon in four successive stages of ionization began to make more sense. With that key she was able to determine the temperatures of the hottest stars, and from that day forward silicon was Payne's favorite element.

WITH THE JOB COMPLETE, PAYNE PROCEEDed to the calculations for which her thesis is most famous: the relative abundances of eighteen elements commonly observed in the atmospheres of various classes of stars. Her guides were Saha's equations and statistical mechanics, especially the seminal work of the English theoretical physicists Edward Milne and Ralph Fowler. She was able to estimate the number of atoms needed to generate a particular spectral feature. Payne was immediately struck that the common elements in the earth's crust were also present in the stars. For elements such as silicon and carbon in the stars, she even found the same relative proportions as exist on earth.

Those findings seemed in accord with trends elsewhere in astrophysics. In 1914, some ten years before Payne's work, Henry Norris Russell, then director of the Princeton University Observatory, had compared the most common materials in the earth's crust with the substances commonly observed in the sun. To a large degree the solar and terrestrial compositions matched. In the 1890s the American physicist Henry A. Rowland, who had prepared an exquisite map of the solar spectrum, had remarked that if the earth's crust were heated to searing solar temperatures, its spectrum would probably look much like the sun's.

HER PHYSICS LAB INSTRUCTOR *would often shout at the female students: "Go and take off your corsets!" certain as he was that the steel frameworks of the corsets would disturb his magnetic equipment.*

But there the similarities ended between Payne's stellar abundances and the relative abundances of the elements on the earth. Two elements stood out as startling exceptions to the rule: "Hydrogen and helium are manifestly very abundant in stellar atmospheres," Payne reported. Indeed, her results suggested that hydrogen alone could be as many as a million times more plentiful in the stars than it is on the earth. Helium in the stars, she noted, was about a thousand times more abundant than the heavier elements.

The winds in physics were blowing against Payne's findings. Eddington, the expert on stellar structure, had figured that the average atomic weight of a star's material was far greater than that of hydrogen, the lightest gas of all. He was so sure his stellar models would not work with high hydrogen abundances that when he applied the quantum rule known as Kramer's law to the interior of the sun and came up with extremely high hydrogen abundances, he assumed the law was wrong. No one—except perhaps a young female graduate student—was quite ready to challenge Eddington's theoretical prowess on stellar interiors.

AT EACH MAJOR STEP IN HER ANALYSES PAYNE wrote a paper describing her findings, completing half a dozen articles before receiving her doctorate in 1925. But she turned conservative when publishing the results on stellar abundances. "In the stellar atmosphere and the meteorite the agreement is good for all atoms that are common to the two," she wrote. "The outstanding discrepancies between the astrophysical and terrestrial abundances are displayed for hydrogen and helium." Then, on the verge of recognizing that the two elements make up the bulk of stellar material, and hence the preponderance of the matter in the universe, Payne pulled back.

Why did she hesitate? "She was bullied," contends Jesse Greenstein, a veteran astronomer now at the California Institute of Technology, and an old friend and colleague of Payne's. "All papers at Harvard, unfortunately, had to be approved by the director, Harlow Shapley." In December 1924 Shapley sent Payne's manuscript to Russell, Shapley's mentor and former teacher at Princeton. A whiz at mathematical computations and a lifelong workaholic prone to nervous breakdowns, Russell was in the vanguard of incorporating modern physics into astronomy. Payne respected and feared Russell, who always seemed to speak with the voice of authority.

Russell at first concluded that Payne's findings were "a very good thing." But five weeks later he had second thoughts, and he wrote the young graduate student, "there remains one very much more serious discrepancy. . . . It is clearly impossible that hydrogen should be a million times more abundant than the metals." In an article sent to *The Proceedings of the National Academy of Sciences* in February 1925, Payne withheld her original conclusion and instead wrote that the abundance calculated for both hydrogen and helium "is improbably high, and is almost certainly not real," a statement reiterated in her doctoral thesis. She toed the party line that a star's makeup basically resembles the composition of the earth's crust.

"Cecilia was a tough cookie," says Greenstein, yet she still acquiesced to Russell's counsel. It is hard for any graduate student to challenge the leaders in the student's field, especially giants such as Russell and Shapley. Without the approval of Russell and Shapley, Payne's thesis would not have been published. Her career and her place in the astronomy community depended on them—and she respected both of them enormously. In fact, Payne had an innocent crush on Shapley, and the two engaged in many long, stimulating scientific discussions, though the director always kept his distance personally. Payne, on the other hand, admitted to a slavish, platonic devotion. "In those days I worshiped Dr. Shapley; I would gladly have died for him," she confessed.

PAYNE WITHHELD HER ORIGINAL *conclusion that hydrogen in stars is a million times more abundant than the metals, and instead wrote that the calculated abundance is "improbably high, and is almost certainly not real."*

Her autobiography does not elaborate at all on the Russell episode and the controversy over her findings. There is only a vague remark that Russell, whose word could make or break a young scientist, vetoed some of her cherished ideas. Yet although she backed down in print, she held to her conviction. Payne visited Cambridge University shortly after her thesis was completed and informed Eddington in a burst of youthful zest that she believed there was far more hydrogen in the stars than any other atom. "You don't mean in the stars," replied Eddington, "you mean on the stars."

IT MAY BE THAT RUSSELL, EDDINGTON AND SHAPLEY were not being obstinate, just cautious. Atomic physics was exploding just as Payne was writing her thesis, and several solar features, such as the sun's opacity, were just beginning to be understood. Knowledge of the atom's structure had only recently moved from the visions of Democritus and Dalton to the ones of Rutherford and Bohr. Finally, Payne was working with crude data, and Russell warned her that hydrogen, because of its simplicity (one proton and one electron), might be giving skewed results.

Payne's hesitation at officially naming hydrogen the prime element hardly diminishes her other accomplishments. Her thesis was the first to combine atomic theory, Saha's new equations and astronomical observations to obtain good estimates of the elemental abundances in the stars, as well as detailed analyses of stellar temperatures and pressures. A number of astronomers would later describe her work as the most brilliant Ph.D. thesis ever written in astronomy. In 1926, at the age of twenty-six, she became the youngest astronomer listed as distinguished in *American Men of Science*. Edwin Powell Hubble, whose observations would soon confirm that the universe was steadily expanding, joked that she was "the best man at Harvard."

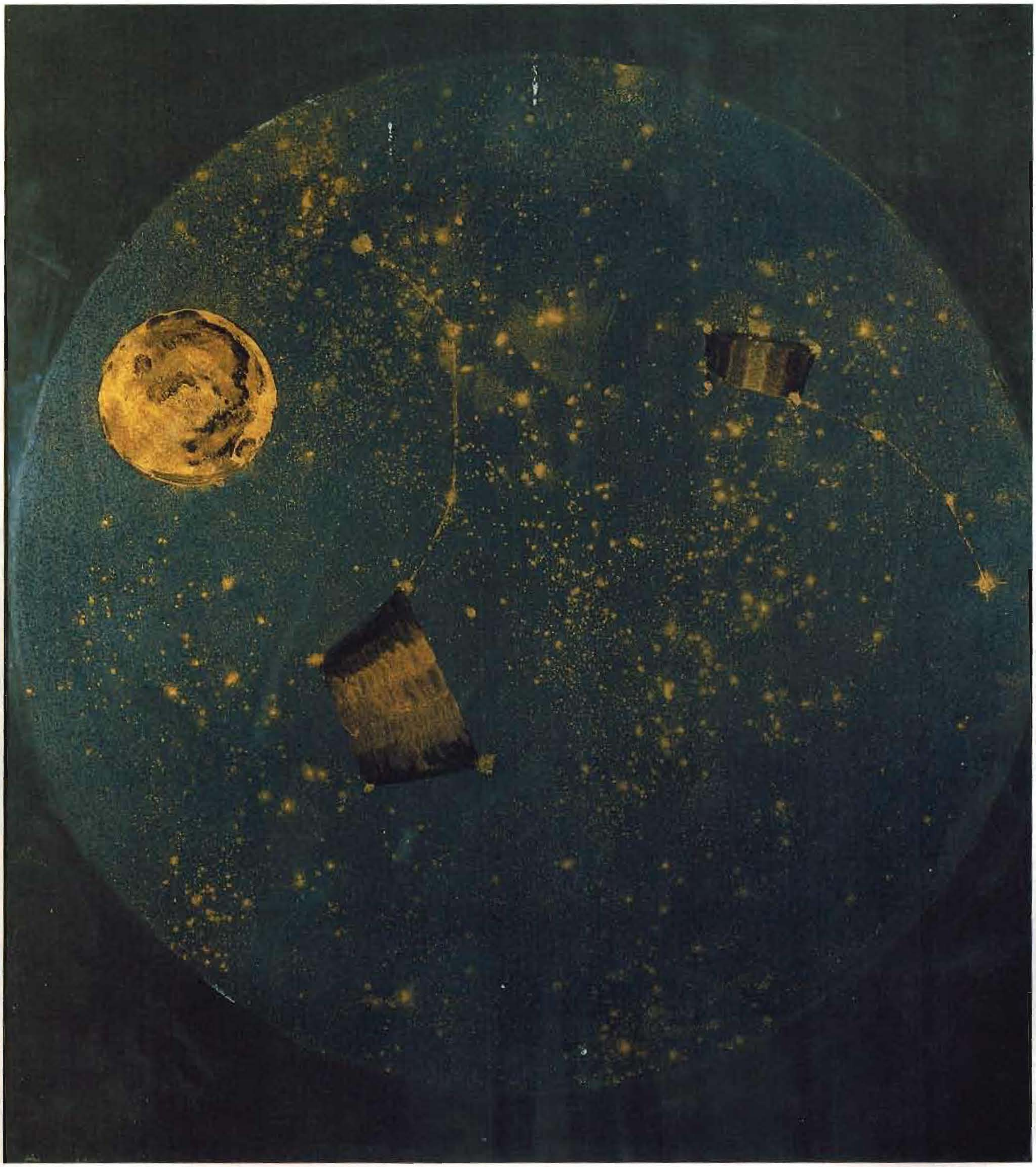
BUT THE MANY RECOGNITIONS WERE SHALLOW triumphs. Mainly because of her sex, a professional position worthy of her expertise eluded her. The historian Peggy Aldrich Kidwell of the National Museum of American History in Washington, D.C., who has written extensively on Payne's work and life, points out that women were either ineligible or simply unwanted for posts at colleges with the best observatories. Payne was paid for a time as Shapley's technical assistant while she lectured and conducted research, but she received no official Harvard appointment until 1938. The courses she taught there were not listed in the university catalogue until 1945. In 1956 she was made a full professor—the first woman at Harvard to attain that rank—perhaps twenty years after a man of her achievements would have earned the position.

Greenstein first met Payne when he was a young Harvard student and she had completed her thesis just a couple of years before. "The obvious discrimination against her as a woman scientist worthy of normal academic recognition exacerbated the stressful life she led," he says. "She was unhappy, emotional. . . . But with me, she was charming and humorous as we exchanged quotations from T. S. Eliot, Shakespeare, the Bible, Gilbert and Sullivan and Wordsworth." She was also, in the words of her daughter, Katherine Haramundanis, a "world traveler, . . . an inspired seamstress, an inventive knitter and a voracious reader"—and a chain-smoker, pun addict and avid card player. Her dignified bearing and imposing stature (five-foot ten) matched her intense personality. A passage from William Wordsworth, the nineteenth-century English poet, sustained her through her trials:

Knowing that Nature never did betray
The heart that loved her.

It is ironic that just four years after Payne's initial foray into stellar compositions, Russell became the principal force in persuading astronomers of the overwhelming preponderance of hydrogen in the sun and the stars. His own conversion followed more detailed observations of the sun, and he rightly noted "a very gratifying agreement" between his findings about the sun and Payne's earlier calculations for hotter stars. But he also left much unsaid. As Kidwell notes, "Russell . . . did not mention that Payne had dismissed her data on hydrogen as probably spurious, nor allude to his role in shaping this conclusion."

All doubts about the preponderance of hydrogen disappeared once the sun's opacity was better understood and as others applied quantum mechanics to the problem. Today it is known that roughly 98 percent of the sun's mass is made up of hydrogen and helium; all the heavier elements make up the remaining 2 percent. In number, hydrogen atoms dominate by far: for every thousand hydrogen atoms there are only sixty-three helium atoms. The next-most abundant elements, oxygen and carbon, contribute half an atom each for every thousand hydrogen atoms.



Arthur Dove, Starry Heavens, *1924*

Russell's original suspicions in 1914 about cosmic abundances were, in the end, partly correct. Except for hydrogen and helium, the ratios among the heavy elements (sparse as they are) in the sun do roughly match the ratios in the earth. That is the signature of the common origin of the sun and the planets out of a swirling cloud of matter some five billion years ago. Through Payne's pioneering efforts and the achievements of those who followed up on her suspicions a new understanding of the composition of the heavens arose: hydrogen became the dominant cosmic ingredient; earthly elements such as carbon, oxygen, nitrogen and iron were just traces of "dirt" in the celestial mix. Nature, it seems, did not betray Payne after all. •

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