The Fires of the Sun

No anniversary of Hiroshima passes without reminding the world of the vast power revealed by the deceptively simple formula $E=mc^2$. But Albert Einstein's famous equation had another career, illuminating, among other things, the origins of the universe and its likely end. In one important chapter of that career a young scientist named Cecilia Payne-Gaposchkin (1900–79) played the leading role.

by David Bodanis

One-and-a-half seconds after the atomic bomb exploded over Hiroshima on the morning of August 6, 1945, the flash of light from the explosion reached the Moon. Some of the light bounced back to Earth; much of the rest continued onward, traveling all the way to the Sun, and then indefinitely beyond. The glare would have been visible from Jupiter.

In the perspective of the galaxy, it was the most insignificant flicker. Our Sun, alone, explodes the equivalent of many millions of such bombs every second. As Albert Einstein and other physicists had long recognized, $E=mc^2$ does not apply just on Earth. It was just a quirk that the accelerated technology and pressures of wartime led to the equation's first applications being focused on the development of weaponry.

Ever since the discovery of radioactivity in the 1890s, researchers had suspected that uranium or a similar fuel might be operating in the wider universe, and in particular, in the Sun to keep it burning. Something that powerful was needed because Charles Darwin's insights as well as findings in geology had shown that the Earth must have been in existence—and warmed by the Sun—for billions of years. Coal or other conventional fuels would not have supplied enough energy to do that.

Astronomers, however, couldn't find any signs of uranium in the Sun. Every element gives off a distinctive visual signal, and the optical device called the spectroscope (because it breaks apart the light spectrum) allows them to be identified. But point a spectroscope at the Sun, and the signals are clear: There is no uranium or thorium or other known radioactively glowing element up there.

What did seem to leap out, in readings from distant stars as well as the Sun, was that there was always iron inside these celestial bodies: lots and lots of metallic bulky iron. By the time Einstein was finally able to leave his job at the Swiss patent office, four years after publishing the 1905 paper setting forth his famous equation, the best evidence suggested that the Sun was about 66 percent pure iron.

This was a disheartening result. Uranium could pour out energy in accord with $E=mc^2$, because the uranium nucleus is so large and overstuffed that it barely holds together. (According to Einstein's equation, mass and energy are interchangeable: The energy [E] in any substance can be found by multiplying its mass [m] by the speed of light [c] squared.) Iron is different. Its nucleus is one of the most perfect and most stable imaginable. A sphere made of iron, even if it were molten or gaseous or ionized iron, could not pour out heat for thousands of millions of years. Suddenly the vision of using $E=mc^2$ and related equations to explain the whole universe was blocked.

The individual who broke that barrier—letting $E=mc^2$ slip the surly bonds of Earth—was a young Englishwoman named Cecilia Payne, who loved seeing how far her mind could take her. Unfortunately, the first teachers she found at Cambridge University when she entered in 1919 had no interest in such explorations. She switched majors, and then switched again, which led to her reading up on astronomy, and when Payne started anything, the effects were impressive. She terrified the night assistant at the university's telescope her first night there, after she'd been reading for only a few days. (He "fled down the stairs," she recalled, gasping, "'There's a woman out there asking questions.'") But she wasn't put off, and a few weeks later, she recalled in her autobiography,* "I bicycled up to the Solar Physics Observatory with a question in my mind. I found a young man, his fair hair tumbling over his eyes, sitting astride the roof of one of the buildings, repairing it. 'I have come to ask,' I shouted up at him, 'why the Stark effect is not observed in stellar spectra.'"

This time her subject did not flee. He

**Cecilia Payne-Gaposchkin: An Autobiography and Other Reflections* (1984), edited by Katherine Haramundanis.

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was an astronomer himself, Edward Milne, and they became friends. Payne tried to pull her art student friends into her astronomical excitements, and even though they might not have understood much of what she was saying, she was the sort of person others liked being around. Her rooms at Newham College were almost always crowded. "When safely lying on her back on the floor (she despises armchairs)," a friend wrote, "she will talk of all things under the sun, from ethics to a new theory of making cocoa."

Ernest Rutherford, whose work helped reveal the structure of the atom, was then a key figure at Cambridge. With men he was bluff and friendly, but with women he was bluff and close to thuggish. He was cruel to Payne at lectures, trying to get all the male students to laugh at this one female in their midst. It didn't stop her from going—she could hold her own with his best students in tutorials—but even 40 years later, retired from her professorship at Harvard University, she remembered the rows of braying young men, nervously trying to do what their teacher expected of them.

Cecilia Payne sets sail for America aboard the Caronia *in 1923.*

But also at the university was Arthur Eddington, a quiet Quaker who was happy to take her on as a tutorial student. Although his reserve never lifted—tea with students was always in the presence of his elderly unmarried sister—the 20-year-old Payne picked up Eddington's barely stated awe at the potential power of pure thought. He liked to show how creatures who lived on a planet entirely shrouded in clouds would be able to deduce the main features of the unseen universe above them. There would have to be glowing spheres up in space, he imagined them reasoning, for a ball of vaporized elements sufficiently large and sufficiently dense would compress the elements inside it to start a nuclear reaction that would make it light up—it would be a sun. These glowing spheres would be dense enough to pull planets swinging around them. If the beings on Eddington's mythical planet ever did find that a sudden wind had blown an opening in their blanket of clouds, they would look up to see a universe of glowing stars with circling planets, just as they'd expected.

It was exhilarating to think that someone on Earth might solve the problem presented by the presence of so much iron in the Sun, and so be able to fulfill Eddington's vision. When Eddington first assigned Payne a problem on stellar interiors, which might at least be a start toward achieving this, "the problem haunted me day and night. I recall a vivid dream that I was at the center of [the giant star] Betelgeuse, and that, as seen from there, the solution was perfectly plain; but it did not seem so in the light of day."

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Even with this kind man's backing, however, a woman couldn't do graduate work in England, so Payne went to Harvard, and there blossomed even more. She found a thesis adviser, Harlow Shapley, who was an up-and-coming astrophysicist. She savored the liberty she found in the dorms, and the fresh topics in the university seminars. She even exchanged her heavy English woolen clothing for the lighter fashions of 1920s America. She was bursting with enthusiasm. And that could have spoiled everything.

Raw enthusiasm is dangerous for young researchers. If you're excited by a new field—keen to join in with what your professors and fellow students are doing—that usually means you'll try to fit in with their approaches to intellectual problems. But students whose work stands out usually have some reason to avoid this, and keep a critical distance. Einstein didn't especially respect his Zurich professors: Most, he thought, were drudges who never questioned the foundations of their teaching. Michael Faraday, the 19th-century discoverer of electromagnetic induction, couldn't be content with explanations that left out the inner feelings of his religion; Antoine Lavoisier was offended by the vague, inexact chemistry handed down by his 18th-century predecessors. For Payne, some of that needed distance came from getting to know her fellow students and their sometimes strange American ways a little better. Shortly after arriving, "I expressed to a friend that I liked one of the other girls in the House where I lived at Radcliffe College. She was shocked: 'But she's a Jew!' was her comment. This frankly puzzled me. . . . I found the same attitude towards those of African descent."

She also got a glimpse of what was going on in the backrooms at the Harvard College Observatory. In 1923, the word computer did not mean an electrical machine. It meant a person whose sole job was to compute. At Harvard, it was applied to ranks of slump-shouldered spinsters in those backrooms. A few of them had once had first-rate scientific talent, but in most cases that had been long since crushed out of them, as they were kept busy measuring star locations or cataloging volumes of previous results. If they married, they could be fired; if they complained about their low salaries, they could be fired as well.

A few of the Harvard "computers," in several decades of bent-back work, succeeded in measuring more than 100,000 spectral lines. But what their findings meant, or how they fit in with the latest developments in physics, was not for them to understand.

Payne was not going to be pushed into their ranks. Spectroscope readings can be ambiguous where they overlap. Payne began to wonder how much the way her professors broke them apart depended on what they already had in mind. For example, try to read the following letters:

not e
v e r y
o new
i l l g
e t i t

It's not easy. But if you start reading it as "Not everyone . . ." then it leaps out. What Cecilia Payne decided on, there in 1920s Boston, was a Ph.D. project that would re-examine the accepted ways of building up spectroscope interpretations. Her work was vastly complicated by the fact that spectroscope lines from the Sun and other stars always include fragments of several elements, and are distorted by the great temperature as well.

An analogy can show what she did. For astronomers convinced there must be lots of iron in the Sun (which seemed reasonable, since there was so much iron on Earth and in asteroids), there would be only one way to read an ambiguous string of lines from a spectroscope. If they came out, for example, as

theysaidironagaien

one would read, "they said iron agaien." There would be no need to worry too much about the odd spelling of agaien—the extra e could be a fault in the spectroscope, or some odd reaction on the Sun, or just a fragment that was slipped in from some other element. There is always something that doesn't fit. But Payne kept an open mind. What if the real message was

t**h**e**y**sai**d**i**ro**na**g**ai**en**

She went through the spectroscope lines over and over again, checking for such ambiguities. Everyone had boosted the lines in one way, to make it read as if they showed the presence of iron. But it wasn't too much of a stretch to boost them differently, to come out with hydrogen.

Even before Payne finished her doctoral thesis, news of her results began to spread among astrophysicists. While the old explanation of the spectroscope data had been that the Sun was two-thirds iron or more, this young woman's interpretation suggested that it was more than 90 percent hydrogen, with most of the rest being helium, which is nearly as light. If she was right, it would change what was understood about how stars burn. Iron is so stable that no one could imagine it might be transformed through $E=mc^2$ to generate heat in the Sun. But who knew what hydrogen might do?

The old guard knew. Hydrogen would do nothing. It wasn't there, it couldn't be there: Their careers—all their detailed calculations, and the power and patronage that stemmed from them—depended on iron being what was in the Sun. After all, hadn't this young woman only picked up the spectroscopic lines from the Sun's outer atmosphere, rather than its deep interior? Maybe her readings were simply confused by the temperature shifts. Her thesis adviser, Shapley, declared her wrong, and then *his* old thesis adviser, the imperious Henry Nonis Russell, declared her wrong, and against him there was very little recourse. Russell was an exceptionally pompous man who would never accept that he could be wrong—and he also controlled most grants and job appointments in astronomy on the East Coast.

For a while Payne tried to fight: repeating her evidence; showing the way her hydrogen interpretation was just as plausible in the spectroscope lines as the iron interpretation; even more, the way new insights—the latest in European theoretical physics—were suggesting a way hydrogen really could power the Sun. It didn't matter. She even tried reaching out to Eddington, but he withdrew, possibly out of conviction, possibly out of caution before Russell—or possibly just from a middle-aged bachelor's fear of a young woman turning to him with emotion. Her friend from her student days at the Cambridge Solar Physics Observatory, the fair-haired young Edward Milne, was by now an established astronomer, and he did try to help, but he didn't have enough power. Letters were exchanged between Payne and Russell, but if she wanted to get her research accepted she'd have to recant. In her published 1925 doctoral thesis she had to insert the humiliating lines: "The enormous abundance [of hydrogen] . . . is almost certainly not real."

A few years later, though, the full power of Payne's work became clear, for independent research by other teams backed her spectroscope reinterpretations. She was vindicated, and her professors were shown to have been wrong.

Although Payne's teachers never really apologized, and tried to thwart her career for as long as they could, the way was now open to applying $E=mc^2$ to explain the fires of the Sun. She had shown that the right fuel was floating up in space that the Sun and all the stars we see actually are great $E=mc^2$ pumping stations. They seem to squeeze hydrogen mass entirely out of existence. But in fact they are simply squeezing it along the equals sign of the equation, so that what had appeared as mass now bursts into the form of billowing, explosive energy. Several researchers made starts on the details, but the main work was done by Hans Bethe, the German-born physicist, who went on to play an important role in the top-secret research at Los Alamos that led to the first atomic bomb.

On Earth, the few hydrogen atoms in our atmosphere just fly past each other. Even if crushed under a mountain of rock, they won't really stick together. But trapped near the center of the Sun, under thousands of miles of weighty substance overhead, hydrogen nuclei can be squeezed close enough together that they will, in time, join to become the element helium.

If this were all that happened, it wouldn't be very important. But it isn't. The mass of four hydrogen nuclei can be written as 1+1+1+1. But when they join together as helium, their sum is not equal to four. Measure a helium nucleus very carefully, and it's about 0.007 less, or just 3.993. That missing mass comes out as roaring energy.

The bomb over Hiroshima destroyed an entire city simply by sucking several ounces of uranium out of existence and transforming it into glowing energy. The Sun, however, pumps 700 million *tons* of hydrogen into pure energy each second. One could see our sun's explosions clearly from the star Alpha Centauri, separated from us by 253 trillion miles of space, and from unimagined planets around stars far along the spiral arm of our galaxy as well.

What of Cecilia Payne? Her thesis adviser, Shapley, hindered her career by making sure she was kept from any of the new electronic equipment coming in. She stayed involved in research as best she could, but he also ensured, as director of the Harvard Observatory, that when she taught a course, it wasn't listed in the Harvard or Radcliffe catalog. As she discovered years later, he had even had her salary paid out of "equipment expenses." When the worst of the sexism ended and a new director took over at the observatory in the postwar era, she had such a heavy teaching load, she wrote, that "there was literally no time for research, a setback from which I have never fully recovered." She did finally win a professorship in 1956, and became a noted writer of textbooks. She was also known as one of the kindest supporters of the next generation at Radcliffe. Married in 1934, Cecilia Payne-Gaposchkin had the pleasure of seeing her only daughter become an astronomer—and of publishing several papers with her. ❑