How the Sun Shines

by JOHN N. BAHCALL

The quest to understand energy production in the Sun frequently leads to fascinating discoveries about neutrinos.

WHAT MAKES the Sun shine? How does it produce the vast amount of energy necessary to support life on Earth? These questions challenged scientists for a hundred and fity years, beginning in the middle of the nineteenth century. Theoretical physicists battled geologists and evolutionary biologists in a heated controversy over who had the correct answer.

Why was there so much fuss about this scientifi puzzle? The nineteenth-century astronomer John Herschel eloquently described the fundamental role of sunshine in all of human life in his 1833 *Treatise on Astronomy*:

> The sun's rays are the ultimate source of almost every motion which takes place on the surface of the earth. By its heat are produced all winds, . . . By their vivifying action vegetables are elaborated from inorganic matter, and become, in their turn, the support of animals and of man, and the sources of those great deposits of dynamical effiiency which are laid up for human use in our coal strata.

In this article, I review the development of our understanding of how the Sun shines, beginning with the nineteenth-century controversy over the age of the Sun. Then I show how seemingly unrelated discoveries in fundamental physics led to a theory of nuclear-energy

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generation in stars, which resolved the controversy over the age of the Sun and explained the origin of solar radiation. Finally, I discuss how experiments designed to test the theory of nuclear energy generation in stars revealed a new conundrumthe mystery of the missing neutrinos.

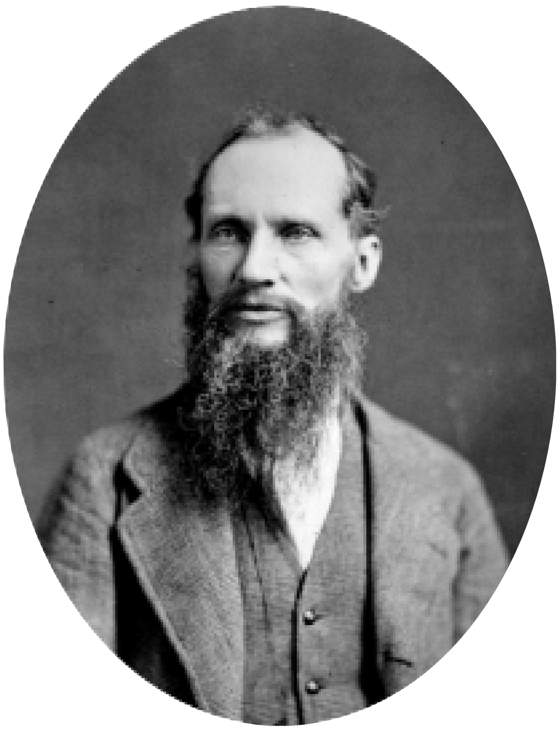
THE AGE OF THE SUN

How old is the Sun? And how does it shine? These questions are two sides of one and the same coin.

The rate at which the Sun radiates energy is easily computed using the measured rate at which energy reaches the Earth's surface and the distance between the two bodies. The total energy that the Sun has radiated away over its lifetime is approximately the product of the rate at which energy is currently being emitted, called the solar luminosity, times the age of the Sun.

The older the Sun is, the greater the total amount of radiated solar energy. The greater the radiated energy, or the older the Sun is, the more diffiult it is to fid an explanation for the source of solar energy.

To appreciate this diffiulty better, consider an illustration of the enormous rate at which the Sun radiates energy. Suppose you leave a cubic centimeter of ice outside on a summer day in such a way that it absorbs all of the sunshine striking it. The sunshine will melt the ice cube



William Thomson, later known as Lord Kelvin (Courtesy AIP Emilio Segrè Visual Archives)

in about 40 minutes. Since this would happen anywhere in space at the Earth's orbit, a huge spherical shell of ice centered on the Sun and 300 million km (187 million miles) in diameter would melt in the same time. Equivalently, an area ten thousand times the area of the Earth's surface and about half a kilometer (a third of a mile) thick would be melted in 40 minutes by the energy pouring out of the Sun. (The luminosity of the Sun exceeds the power generated by 100,000,000,000,000,000 1-GW power plants.)

Nineteenth-century physicists believed gravitation to be the energy source for solar radiation. In an influential 1854 lecture, Hermann von Helmholtz, a German professor of physiology who became a distinguished researcher and physics professor, proposed that the origin of the Sun's enormous radiated energy is the gravitational contraction of its huge mass. He echoed Julius Mayer (another German physician) and J. J. Waterston, who had earlier suggested that the origin of solar radiation is the conversion of gravitational energy into heat. Von Helmholtz and Mayer helped to elucidate the law of conservation of energy, which states that energy can be transformed from one form into another but the total amount of energy never changes.

Biologists and geologists considered the effects of solar radiation, while physicists concentrated on the origin of the radiated energy. In 1859 Charles Darwin, in the first edition of *On The Origin of the Species by Natural Selection*, made a crude calculation of the age of the Earth by estimating how long it would take erosion occurring at the then-observed rate to wash away the Weald, a great valley that stretches between the North and South Downs across the south of England. He obtained a time for the "denudation of the Weald" in the range of 300 million years, which was apparently long enough for natural selection to have produced the astounding range of species that exist on Earth.

Darwin's estimate of a minimum duration of geological activity implied a minimum amount of energy that the Sun had radiated.

Firmly opposed to Darwinian natural selection, William Thompson, later Lord Kelvin, was then a professor at the University of Glasgow and one of the great physicists of the nineteenth century. In addition to his many contributions to applied science and to engineering, Thompson helped to formulate the second law of thermodynamics and set up the absolute temperature scale, which was subsequently named the Kelvin scale in his honor. The second law states that heat naturally flows from a hotter to a colder body, not vice versa. Kelvin therefore realized that the Sun and the Earth will cool unless there is an external energy source.

Like Helmholtz, Kelvin believed that the Sun's luminosity was produced by the conversion of gravitational energy into heat. In 1854 he suggested that the Sun's heat might be produced by the impact of meteors continually falling onto its surface. Astronomical evidence forced him to modify his hypothesis, and he then argued that the primary source of the energy available to the Sun was the gravitational energy of the primordial meteors from which it had been formed. With great authority and eloquence Lord Kelvin declared in 1862:

> That some form of the meteoric theory is certainly the true and complete explanation of solar heat can scarcely be doubted, when the following reasons are considered: (1) No other natural explanation, except by chemical action, can be conceived. (2) The chemical theory is quite insufficient, because the most energetic chemical action we know, taking place between substances amounting to the whole sun's mass, would only generate about 3,000 years' heat. (3) There is no difficulty in accounting for 20,000,000 years' heat by the meteoric theory.

He continued attacking Darwin's estimate directly, asking, "What then are we to think of such geological estimates as [Darwin's] 300,000,000 years for the 'denudation of the Weald'?" Believing Darwin had overestimated the Earth's age, Kelvin also thought that Darwin was wrong about the time available for natural selection.

Lord Kelvin estimated the lifetime of the Sun, and by implication the Earth's age, as follows: He calculated the gravitational energy of an object with a mass equal to the Sun's mass and a radius equal to the Sun's radius, then divided the result by the rate at which the Sun radiates away energy. This calculation yielded a lifetime of just 30 million years—only one tenth of Darwin's estimate. The corresponding estimate for the lifetime sustainable by release of chemical energy was much smaller because chemical processes generate comparatively little energy.

During the nineteenth century you could get very different estimates for the age of the Sun depending upon whom you asked. Prominent theoretical physicists argued, based upon the sources of energy known at that time, that the Sun was at most a few tens of million years old. By contrast, many geologists and biologists concluded that the Sun must have been shining for at least several hundreds of millions of years in order to account for geological changes and the evolution of living things. Thus the age of the Sun, and the origin of solar energy, were important questions not only for physics and astronomy, but also for geology and biology.

Darwin was so shaken by the power of Kelvin's analysis and by the authority of his theoretical expertise, that in the last editions of *On The Origin of the Species* he eliminated all mention of specific time scales. He wrote in 1869 to Alfred Russel Wallace, the codiscoverer of natural selection, complaining about Lord Kelvin, "Thomson's views on the recent age of the world have been for some time one of my sorest troubles."

Today we know that Lord Kelvin was wrong and the geologists and evolutionary biologists were right. Radioactive dating of meteorites shows that the Sun is 4.6 billion years old, and the Earth is almost as old.

An analogy may help us understand what was wrong with Kelvin's analysis. Suppose a friend tries to figure out how long your laptop computer has been operating. A plausible estimate might be no more than a few hours, since that is the maximum duration a battery can supply the required amount of power. The flaw in this analysis is his assumption that your computer is powered only by a battery. This estimate of a few hours would fall far short of reality if your computer was also powered from an electric outlet in the wall. The flaw in Kelvin's analysis was his assumption that only gravitational energy powers the Sun.

Since nineteenth-century theoretical physicists knew nothing about the possibility of transforming nuclear mass into energy, they calculated a maximum age for the Sun that was far too short. Nevertheless, Kelvin and his colleagues made a lasting contribution to the sciences of astronomy, geology, and biology by insisting that valid inferences in all fields of research must be consistent with the fundamental laws of physics.

GLIMPSES OF THE SOLUTION

The turning point in this battle between theoretical physicists and empirical geologists and biologists occurred in 1896. In the course of an experiment designed to study X rays, discovered the previous year by Wilhelm Roentgen, Henri Becquerel stored some uranium-covered plates in a desk drawer atop photographic plates wrapped in dark paper. Upon developing the photographic plates, he found to his surprise strong images of the uranium crystals. He had discovered natural radioactivity, due to nuclear transformations of uranium atoms.

The significance of Becquerel's discovery became apparent in 1903, when Pierre Curie and his young assistant, Albert Laborde, announced that radium salts constantly release heat. The most extraordinary aspect of this new discovery was that radium gave off heat without cooling down to the temperature of its surroundings. This radiation had to have a previously unknown source of energy. William Wilson and George Darwin almost immediately proposed that similar radioactivity might be the source of the Sun's radiated energy.

Ernest Rutherford, then a professor of physics at McGill University in Montreal, soon discovered the enormous energy released by the emission of alpha particles from radioactive substances. In 1904 he announced:

> The discovery of the radioactive elements, which in their disintegration liberate enormous amounts of energy, thus increases the possible limit of the duration of life on this planet, and allows the time claimed by the geologist and biologist for the process of evolution.

The discovery of radioactivity opened up the possibility that nuclear energy might be the source of solar radiation, freeing theorists from reliance in their calculations on gravitational energy. However, subsequent astronomical observations showed that the Sun does not contain much radioactive material, but is instead mostly gaseous hydrogen. Moreover, the rate at which radioactivity delivers energy does not vary with temperature, while observations of stars suggested that the amount of energy radiated by a star does indeed depend sensitively upon its interior temperature. Something other than radioactivity was required to release nuclear energy within a star.

The next fundamental advance came once again from an unexpected direction. In 1905 Albert Einstein derived his famous relation between mass and energy, $E = mc^2$, as a consequence of the special theory of relativity. This equation showed that a tiny amount of mass could, in principle, be converted into a tremendous amount of energy. Einstein's famous equation generalized and extended the nineteenth-century law of energy conservation of Helmholtz and Mayer to include the conversion of mass into energy.

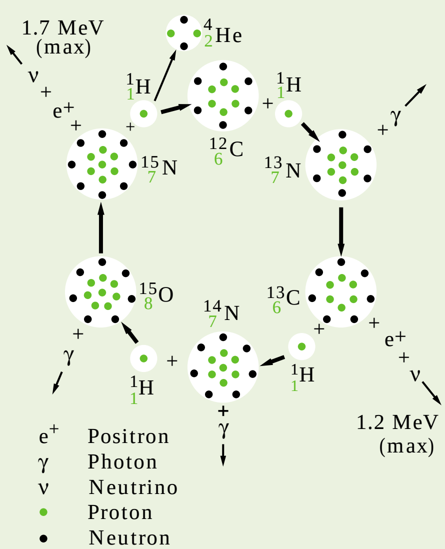
What was the connection between Einstein's equation and the Sun's energy source? The answer was not immediately obvious. Astronomers did their part by defining the constraints that observations of stars imposed on the possible explanations of stellar energy generation. In 1919 Henry Norris Russell, the leading theoretical astronomer in the United States, summarized the astronomical hints about the nature of the stellar energy source. The most important clue, he stressed, was the high temperature in the interiors of stars.

In 1920 Francis Aston discovered the key experimental piece of the puzzle. He made precise measurements of the masses of many different atoms, among them hydrogen and helium. Aston found that four hydrogen nuclei were slightly heavier than a helium nucleus.

The importance of these measurements was immediately recognized by Sir Arthur Eddington, the brilliant English astrophysicist. He argued in his 1920 presidential address to the British Association for the Advancement of Science that Aston's determination of the mass

The CNO Cycle

FOR STARS HEAVIER than the Sun, theoretical models show that the CNO (carbon-nitrogen-oxygen) cycle of nuclear fusion is the dominant source of energy generation. The cycle results in the fusion of four hydrogen nuclei (^{1}H, protons) into a single helium nucleus (^{4}He, alpha particle), which supplies energy to the star in accordance with Einstein's equation. Ordinary carbon, ^{12}C, serves as a catalyst in this set of reactions and is regenerated. Only relatively low-energy neutrinos are produced in this cycle. The figure is adapted from John N. Bahcall, "Neutrinos from the Sun," *Scientific American*, 221, 1 (1969) 28–37.



difference between hydrogen and helium meant that the Sun could shine by converting hydrogen atoms into helium. This thermonuclear fusion would (according to Einstein's relation between mass and energy) release the energy equivalent to 0.7 percent of the hydrogen mass. In principle, such a process could allow the Sun to shine for about 100 billion years.

In a frighteningly prescient insight, Eddington went on to remark about the connection between stellar energy generation and the future of humanity:

> If, indeed, the sub-atomic energy in the stars is being freely used to maintain their great furnaces, it seems to bring a little nearer to fulfillment our dream of controlling this latent power for the well-being of the human race—or for its suicide.

UNDERSTANDING THE PROCESS

The next big step in understanding how stars produce energy resulted from applying quantum mechanics to the explanation of nuclear radioactivity. This application was made without any reference to what happens in stars. Two particles with the same sign of electrical charge will repel each other. According to classical physics, the probability that two positively charged particles can get very close together is essentially zero. But, some things that cannot happen in classical physics can occur in the quirky microscopic world described by quantum mechanics.

In 1928 George Gamow, the Russian-American theoretical physicist, derived a quantum-mechanical formula that predicted that two charged particles could occasionally overcome their mutual electrostatic repulsion and approach one another extremely closely. This quantum-mechanical probability, now known as the "Gamow factor," is widely used to explain the measured rates of certain radioactive decays.

In the decade that followed, Robert Atkinson and Fritz Houtermans and later George Gamow and Edward Teller used the Gamow factor to derive the rate of nuclear reactions at the high temperatures believed to exist in the interiors of stars. It allowed them to estimate how often two hydrogen nuclei would get close enough together to fuse and thereby release energy.

In 1938 Carl Friedrich von Weizsäcker came close to solving the problem of how some stars shine. He discovered a nuclear cycle, now known as the carbon-nitrogen-oxygen (CNO) cycle (see box on previous page), in which hydrogen nuclei could fuse using carbon as a catalyst. But von Weizsäcker did not investigate the rate at which energy would be produced in a star by the CNO cycle, nor did he study the crucial dependence of this reaction upon stellar temperature.

The scientific stage had been set for the entry of Hans Bethe, the acknowledged master of nuclear physics. He had just completed a classic set of three papers in which he reviewed and analyzed all that was then known about nuclear physics, works known among his colleagues as "Bethe's bible." Gamow assembled a small conference of physicists and astrophysicists in Washington, DC, to discuss the state

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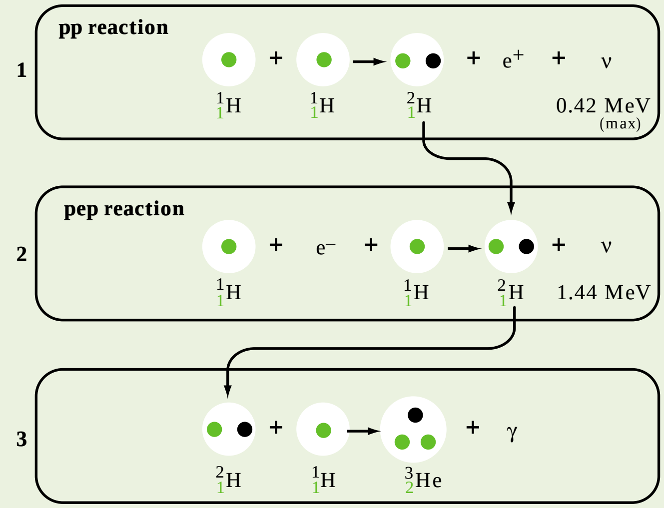
Hans Bethe in 1935, Ann Arbor, Michigan (Courtesy AIP Emilio Segrè Visual Archives)

The pp Cha

IN THEORETICAL MODELS of the Sun, the *pp* chain of nuclear reactions illustrated here is the dominant source of energy production. Each reaction is labeled by a number to the left of the box in which it is contained. In reaction 1, two hydrogen nuclei (^{1}H, protons) are fused to produced a heavy hydrogen nucleus (^{2}H, a deuteron). This is the usual way nuclear burning gets started in the Sun. On rare occasions, the process is started by reaction 2. Deuterons produced in reactions 1 and 2 fuse with protons to produce light nuclei of helium (^{3}He). At this point, the *pp* chain breaks into three branches, whose relative frequencies are given on the right. The net result of this chain is the fusion of four protons into a single ordinary helium nucleus (^{4}He) with energy being released to the star in accordance with Einstein's equation. Neutrinos are emitted in some of these fusion processes. Their energies are shown in the figure in units of millions of electron volts (MeV).



[Figures adapted from John N. Bahcall, "Neutrinos from the Sun," Scientific American*, 221, 1 (1969) 28–37.]*

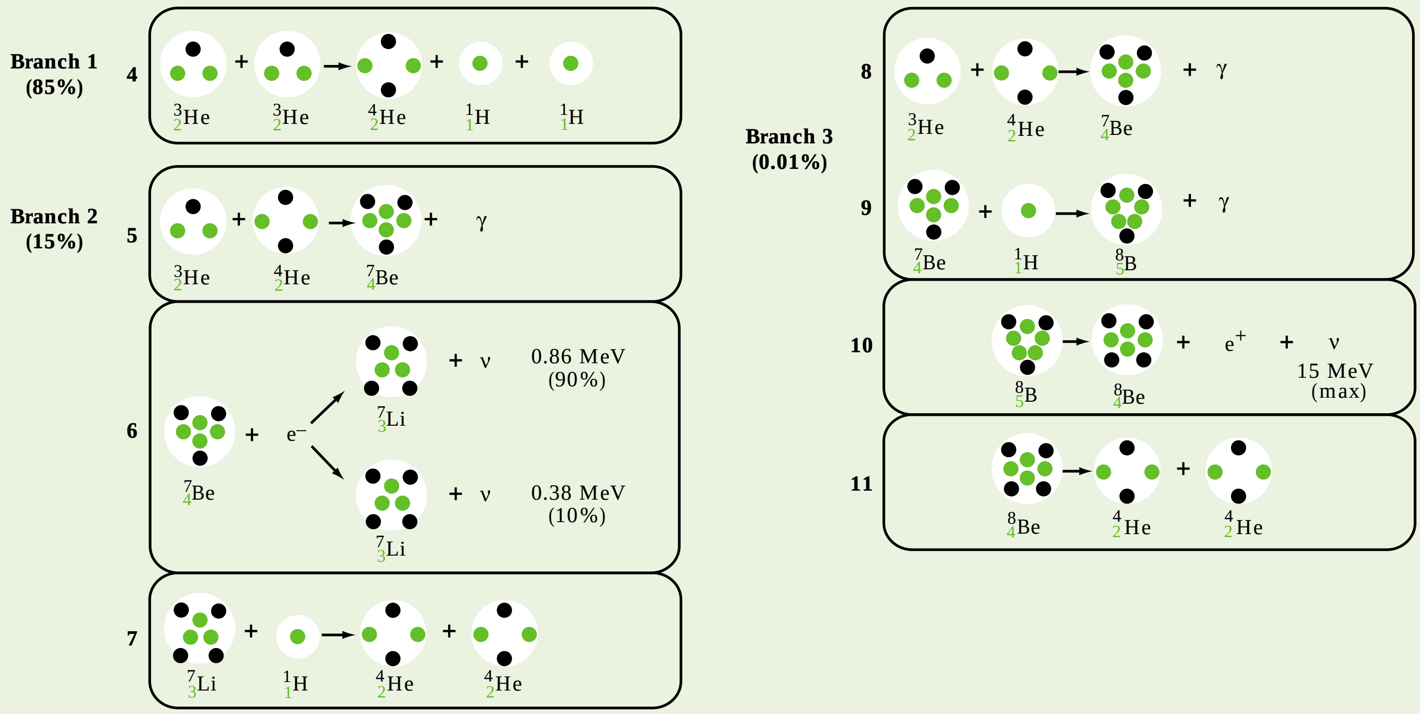
of knowledge, and the unsolved problems, concerning the internal constitution of the stars. In the course of the next six months, Bethe worked out the basic nuclear processes by which hydrogen is burned (fused) into helium in stellar interiors. Hydrogen is the most abundant constituent of the Sun and similar stars, and indeed the most abundant element in the Universe.

Bethe described the results of his calculations in a 1939 paper entitled "Energy Production in Stars." He analyzed the different possibilities for nuclear fusion reactions and selected as most important the two processes that we now believe are responsible for sunshine. One process, the so-called *pp* chain (see box above), builds helium out of hydrogen and is the dominant energy source in stars like the Sun and less massive stars. The second process is the CNO cycle considered by von Weizsäcker; it is most important in stars that are more massive than the Sun. Bethe estimated the central temperature of the Sun, obtaining a value within 20 percent of the value (16 million degrees kelvin) that we currently believe is correct.* Moreover, he showed that his calculations led to a relation between the mass and luminosity of stars that was in agreement with astronomical observations.

**According to the modern theory of stellar evolution, the Sun is heated to the enormous temperatures at which nuclear fusion can occur by gravitational energy released as the solar mass contracts from an initially large gas cloud. Thus Kelvin and other nineteenth-century physicists were partially right; the release of gravitational energy ignited nuclear energy generation in the Sun.*

In the first two decades after the end of World War II, many important details were added to Bethe's theory of nuclear burning in stars. Distinguished physicists and astrophysicists, especially Al Cameron, William Fowler, Fred Hoyle, Edwin Salpeter, Martin Schwarzschild, and their experimental colleagues, returned eagerly to the question of how stars like the Sun generate energy. From Bethe's work, the answer was known in principle: the Sun produces energy by burning hydrogen. According to this theory, the solar interior

in Reaction



is a sort of controlled thermonuclear bomb on a gigantic scale (The sensitive dependence of the Gamow factor upon the relative energy of the two charged particles is, we now understand, what provides the temperature "thermostat" for stars.) The theory leads to the successful calculation of the observed luminosities of stars similar to the Sun and provides the basis for our current understanding of how stars shine and evolve over time.

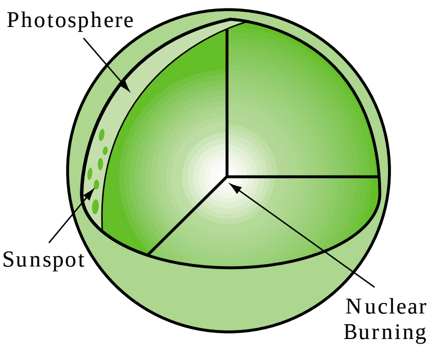
William Fowler led a team of colleagues in his Caltech Kellogg Laboratory and inspired physicists throughout the world to measure or calculate the most important details of the *pp* chain and the CNO cycle. There was plenty of work to do, and the experiments and calculations were difficult. But the work got done because understanding the specifics of solar energy generation was so interesting. Most of the efforts of Fowler and his colleagues soon shifted to the problem of how the heavier elements are produced in stars.

DISCOVERY, CONFIRMATION, AND SURPRISE

Science progresses as a result of the clash between theory and experiment—between speculation and measurement. In the same lecture in which he first discussed the burning of hydrogen nuclei in stars, Eddington remarked:

> I suppose that the applied mathematician whose theory has just passed one still more stringent test by observation ought not to feel satisfaction, but rather disappointment—'Foiled again! This time I had hoped to find a discordance which would throw light on the points where my model could be improved.'

Is there any way to test the theory that the Sun shines because very deep in its interior hydrogen is burned into helium? At first thought, it seems impossible to make a direct test of the nuclear-burning hypothesis. Light takes tens of thousands of



A cross section of the Sun. The features that are usually studied by astronomers with normal telescopes that detect light are labeled on the outside, for example, sunspots. Neutrinos enable us to look deep inside the Sun, into the solar core where nuclear burning occurs.

years to leak out from the center of the Sun to its surface. When it finally emerges, this light tells us mainly about the conditions in the outmost regions. Nevertheless, there is a way of "seeing" into the solar interior using neutrinos—exotic particles that were first proposed in 1930 by Wolfgang Pauli and finally detected in 1956 by Clyde Cowan and Frederick Reines.

A neutrino is a subatomic particle that interacts very weakly with matter and travels at essentially the speed of light. Neutrinos are produced in stars when hydrogen nuclei are fused to form helium nuclei; neutrinos are also produced on Earth in particle accelerators, nuclear reactors, and natural radioactivity. Based upon the work of Bethe and his colleagues, we believe that the process by which stars like the Sun generate energy can be described by the relation

$$4\,{}^1\mathrm{H} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu + \text{energy},$$

in which four hydrogen nuclei (^{1}H) are fused into a single helium nucleus (^{4}He) plus two positrons (e^+) and two neutrinos (ν) plus energy. This process releases energy to the star since, as Aston showed, four hydrogen atoms are heavier than a helium atom. (In fact, they are heavier than a helium atom plus two positrons and two neutrinos.) The same nuclear reactions that supply the energy of the Sun's radiation also produce telltale neutrinos that we can try to detect in the laboratory.

Because of their weak interactions, however, neutrinos are difficult to detect. How difficult? A solar neutrino passing through the entire Earth has less than one chance in a trillion of interacting with terrestrial matter. According to standard solar theory, about a hundred billion solar neutrinos pass through your thumbnail every second, and you don't even notice them. Neutrinos can travel unaffected through a hundred light-years thickness of iron. But if you put enough material in the way of a sufficiently high flux of neutrinos, as Cowan and Reines showed, you can observe occasional interactions.

In 1964 Raymond Davis Jr. and I proposed that an experiment with 100,000 gallons of cleaning fluid (perchloroethylene, which is mostly composed of chlorine) could provide a critical test of the idea that nuclear fusion reactions are the ultimate source of solar radiation. We argued that if our understanding of nuclear processes in the interior of the Sun was correct, then solar neutrinos would be captured at a rate that Davis could measure with a large tank filled with this fluid. When neutrinos interact with chlorine, they occasionally produce a radioactive isotope of argon. Davis had shown that he could extract tiny amounts of neutrino-produced argon from large quantities of perchloroethylene. To do the solar neutrino experiment, he had to be spectacularly clever since according to my calculations, only a few atoms would be produced per week in a huge volume of cleaning fluid the size of an Olympic swimming pool!

Our sole motivation for urging this experiment was to use neutrinos to "enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear-energy generation in stars." We did not anticipate some of the most interesting aspects of this proposal.

Davis performed the experiment and in 1968 announced the first results: he observed fewer neutrinos than predicted. As the experiment and the theory were refined, the disagreement appeared more and more robust. Scientists rejoiced that solar neutrinos had been detected but worried about why there were fewer neutrinos than expected.

What was wrong? Was our understanding of how the Sun shines incorrect? Had I made an error in calculating the rate at which solar neutrinos would be captured in Davis's tank? Was the experiment wrong? Or, did something happen to the neutrinos after they were created in the Sun?

Over the next twenty years, many different possibilities were examined by hundreds of physicists, chemists, and astronomers. Both the experiment and the theoretical calculation appeared to be correct.

Once again experiment rescued pure thought. In 1986 Japanese physicists led by Masatoshi Koshiba and Yoji Totsuka, together with their American colleagues Eugene Beier and Alfred Mann, reinstrumented a huge tank of water designed to measure the stability of matter. The experimenters increased the sensitivity of their detector so that it could also serve as a large underground observatory of solar neutrinos. Their goal was to explore the reason for the quantitative disagreement between the predicted and the measured rates in Davis's chlorine experiment.

The new experiment (Kamiokande) in the Japanese Alps also detected solar neutrinos. Moreover, it confirmed that the neutrino rate was substantially less than predicted by standard physics and standard models of the Sun; it also clearly demonstrated that the detected neutrinos indeed came from the Sun. Subsequently experiments in Russia (called SAGE, led by Vladimir Gavrin), Italy (GALLEX and later GNO led by Till Kirsten and Enrico Belotti, respectively), and in Japan (Super-Kamiokande, led by Yoji Totsuka and Yoichiro Suzuki), each with different characteristics, all observed neutrinos from the solar interior. In each detector, the number of neutrinos observed was significantly lower than standard theories predicted.

What do all of these experimental results tell us? Neutrinos produced in the center of the Sun have been detected in five experiments. Their detection proves that the source of the energy that the Sun radiates is indeed the fusion of hydrogen nuclei in the solar interior. The nineteenth-century debate between theoretical physicists, geologists, and biologists has been settled empirically.

From an astrophysical perspective, the agreement between neutrino observations and theory is good. The observed energies of the solar neutrinos match the predicted values. The rates at which neutrinos are detected are less than predicted but by factors of only 2–3. Since the predicted neutrino flux at the Earth depends approximately upon the 25th power of the core temperature of the Sun, the agreement that has been achieved indicates that we have empirically measured this temperature of the Sun to an accuracy of a few percent. If someone had told me in 1964 that number of solar neutrinos observed would be within a factor of 3 of the predicted value, I would have been astonished and delighted.

In fact, the agreement between normal astronomical observations (using light rather than neutrinos) and theoretical calculations of solar characteristics is much more precise. Studies of the internal structure of the Sun based on observations of solar vibrations show that the standard solar model predicts temperatures at the Sun's core that are consistent with observations to an accuracy of better than 0.1 percent. Then what can explain the disagreement by a factor of 2 to 3 between the measured and the predicted solar neutrino rates?

Physicists and astronomers were once again forced to reexamine their theories. This time, the discrepancy was not between different estimates of the Sun's age, but rather between predictions based upon a widely accepted theory and direct measurements of particles produced by nuclear burning in the Sun's interior. This situation was sometimes referred to as the "mystery of the missing neutrinos" or, in language that sounded more scientific, "the solar neutrino problem."

As early as 1969, two scientists working in Russia, Bruno Pontecorvo and Vladimir Gribov, had proposed that the discrepancy between theory and the first solar neutrino experiment could be due to an inadequacy in the textbook description of particle physics, rather than in the standard solar model. (Incidentally, Pontecorvo was also the first person to propose using a chlorine detector to study neutrinos.) Gribov and Pontecorvo suggested that neutrinos possess a dual personality—that they oscillate back and forth between different states or types. Physicists call this propensity “neutrino oscillations.”

According to this idea, neutrinos are produced in the Sun in a mixture of individual states: they have a sort of split personality. The individual states have different, small masses, rather than the zero masses attributed to them by standard particle theory. As they travel to the Earth, neutrinos oscillate between the easier-to-detect neutrino state (the electron neutrino ν_e) and a more difficult-to-detect neutrino state. Davis’s chlorine experiment could only detect neutrinos in the easier-to-observe state. If many of the neutrinos arrive at Earth in a state that is difficult to observe, then they are not counted. It seems as if some or many of the neutrinos have vanished, explaining the apparent mystery of the missing neutrinos.

Building upon this idea, Lincoln Wolfenstein in 1978 and Stanislav Mikheyev and Alexei Smirnov in 1985 showed that matter can affect neutrinos as they travel through the Sun. If Nature has chosen to give them masses in a particular range, this effect can increase the oscillation probability of the neutrinos.

Neutrinos are also produced by the collisions of cosmic rays with particles in the Earth’s atmosphere. In 1998 the Super-Kamiokande team announced that they had observed oscillations among atmospheric neutrinos. This finding provided indirect support for the theoretical idea that solar neutrinos oscillate among different states. Many scientists working on the subject believe that, in retrospect, we have had evidence for oscillations of solar neutrinos since 1968.

But we do not yet know what causes the multiple personality disorder of solar neutrinos. The answer to this question may provide a clue to physics beyond the current Standard Model of elementary particles and their interactions. Does the identity change occur while the neutrinos are traveling to the Earth from the Sun, as originally proposed by Gribov and Pontecorvo? Or does matter induce solar neutrinos to flip out”? Experiments under way in Canada, Italy, Japan, Russia, and the United States are attempting to pin down the exact cause of solar neutrino oscillations, by measuring their masses and how they transform from one type into another. Non-zero neutrino masses may provide a clue to a still undiscovered realm of physical theory.

A WONDERFUL MYSTERY

Nature has written a wonderful mystery story. The plot continually changes and the most important clues come from seemingly unrelated investigations. These sudden and drastic changes of scene appear to be Nature’s way of revealing the unity of all fundamental science.

The mystery began in the middle of the nineteenth century with the puzzle: How does the Sun shine? Almost immediately, the plot shifted to questions about how fast natural selection occurs and the rate at which geological formations are created. One of the best theoretical physicists of the nineteenth century gave the wrong answer to all these questions. The first hint of the correct answer came, at the very end of the nineteenth century, from the discovery of radioactivity with accidentally darkened photographic plates.

The right direction in which to search for the detailed solution was revealed by the 1905 discovery of the special theory of relativity, by the 1920 measurement of the nuclear masses of hydrogen and helium, and by the 1928 quantum-mechanical explanation of how charged particles can get close to one another. These crucial investigations were not directly related to the study of stars.

By the middle of the twentieth century, nuclear physicists and astrophysicists could calculate theoretically the rate of nuclear burning in the interiors of stars like the Sun. But, just when we thought we had Nature figured out, experiments showed that fewer solar neutrinos were observed at Earth than were predicted by the standard models of how stars shine and how subatomic particles behave.

As the twenty-first century begins, we have learned that solar neutrinos tell us not only about the interior of the Sun, but also something about the nature of neutrinos themselves. No one knows what surprises will be revealed by the new solar neutrino experiments currently under way. The richness with which Nature has written her mystery, in an international language that can be read by curious people of all nations, is beautiful, awesome, and humbling.