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# *Beam Line*



# Beam Line

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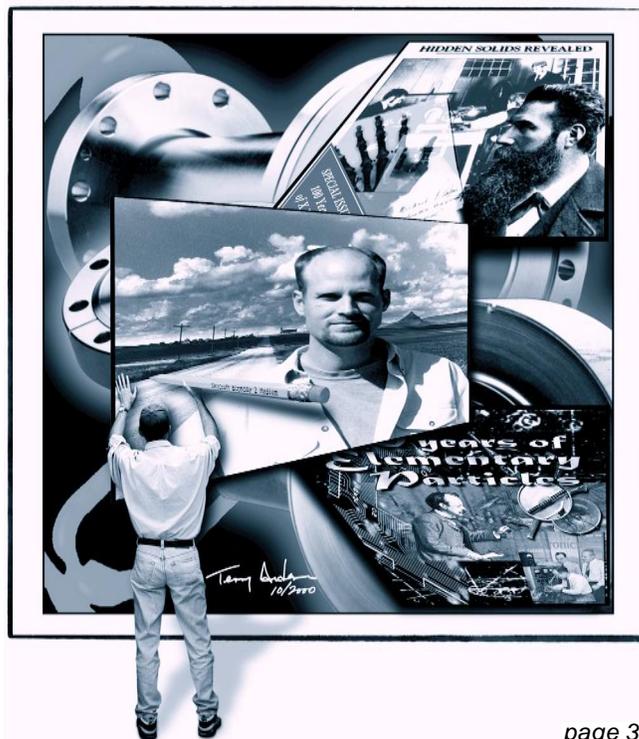
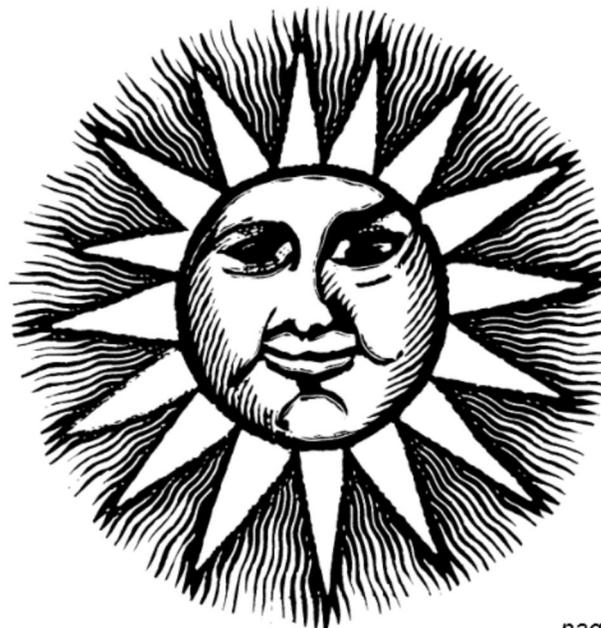
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Cover: Installation of the  $D\bar{0}$  detector at the Fermilab Tevatron Collider. The photograph shows part of the detector designed to trigger on muons, together with the shielding which encases the beam line entering the detector (red blocks in the center). These detector elements were built in Protvino, Russia, and traveled 5000 miles before they were installed in  $D\bar{0}$ .



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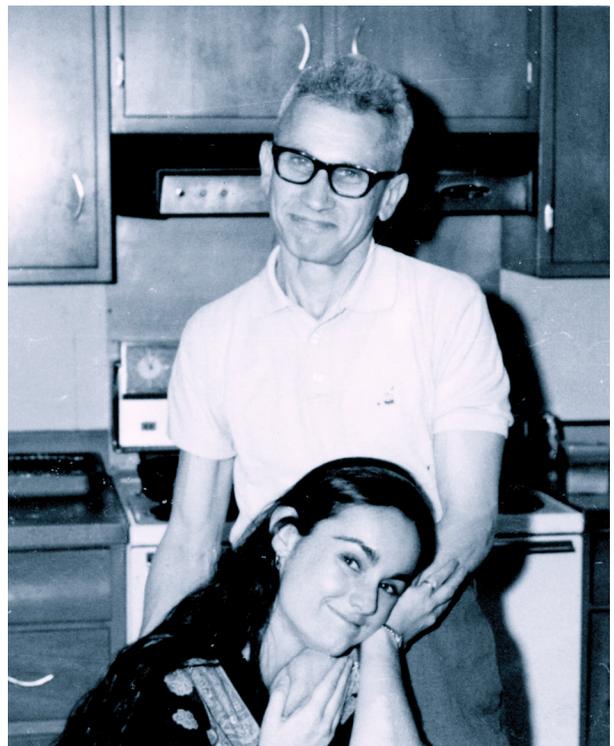
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# How the Sun Shines

by JOHN N. BAHCALL

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

**W**HAT 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 fifty 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 scientific 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 efficiency 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





*(First published at Nobel e-Museum, [www.nobel.se](http://www.nobel.se))*

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 conundrum—the 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 difficult it is to find an explanation for the source of solar energy.

To appreciate this difficulty 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 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.

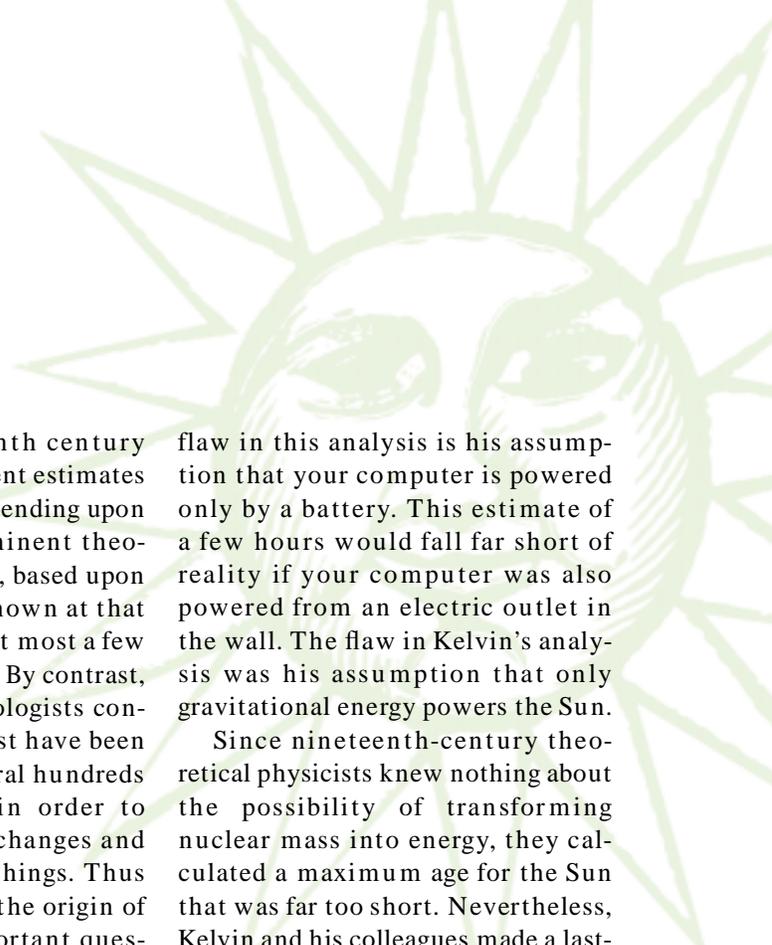
Biologists and geologists considered the effects of solar radiation, while physicists concentrated on the origin of the radiated energy. In 1859 Charles Darwin, in the first edition of *On The Origin of the Species by Natural Selection*, made a crude calculation of the age of the Earth by estimating 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 Thomson, 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, Thomson 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.

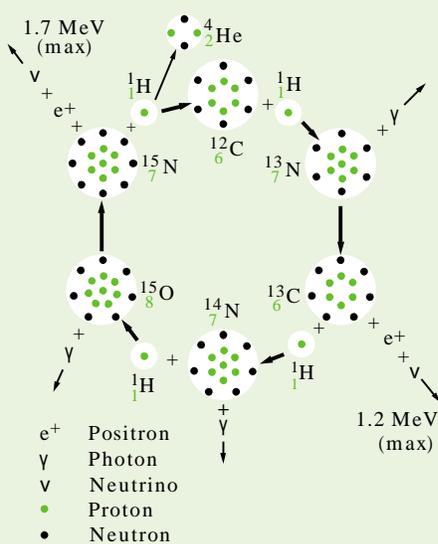
What was the connection between Einstein's equation and the Sun's energy source? The answer was not immediately obvious. Astronomers did their part by defining the constraints that observations of stars imposed on the possible explanations of stellar energy generation. In 1919 Henry Norris Russell, the 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

**F**OR 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 ( $^1\text{H}$ , protons) into a single helium nucleus ( $^4\text{He}$ , alpha particle), which supplies energy to the star in accordance with Einstein's equation. Ordinary carbon,  $^{12}\text{C}$ , 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

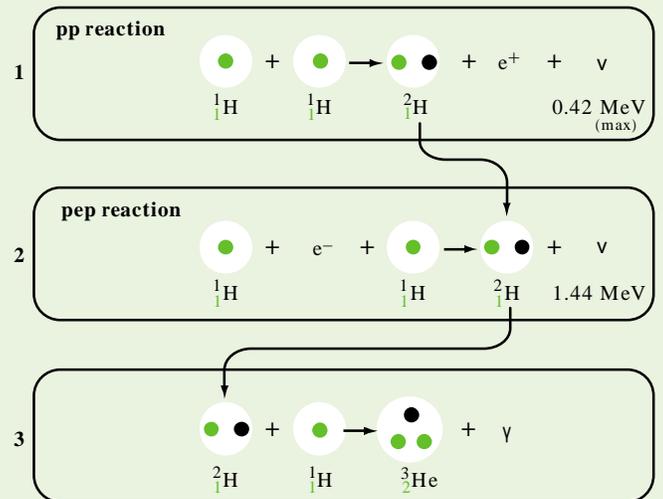


S. A. Goudsmit

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

# The pp Cha

**I**N 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 ( ${}^1\text{H}$ , protons) are fused to produce a heavy hydrogen nucleus ( ${}^2\text{H}$ , 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 ( ${}^3\text{He}$ ). 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 ( ${}^4\text{He}$ ) 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,

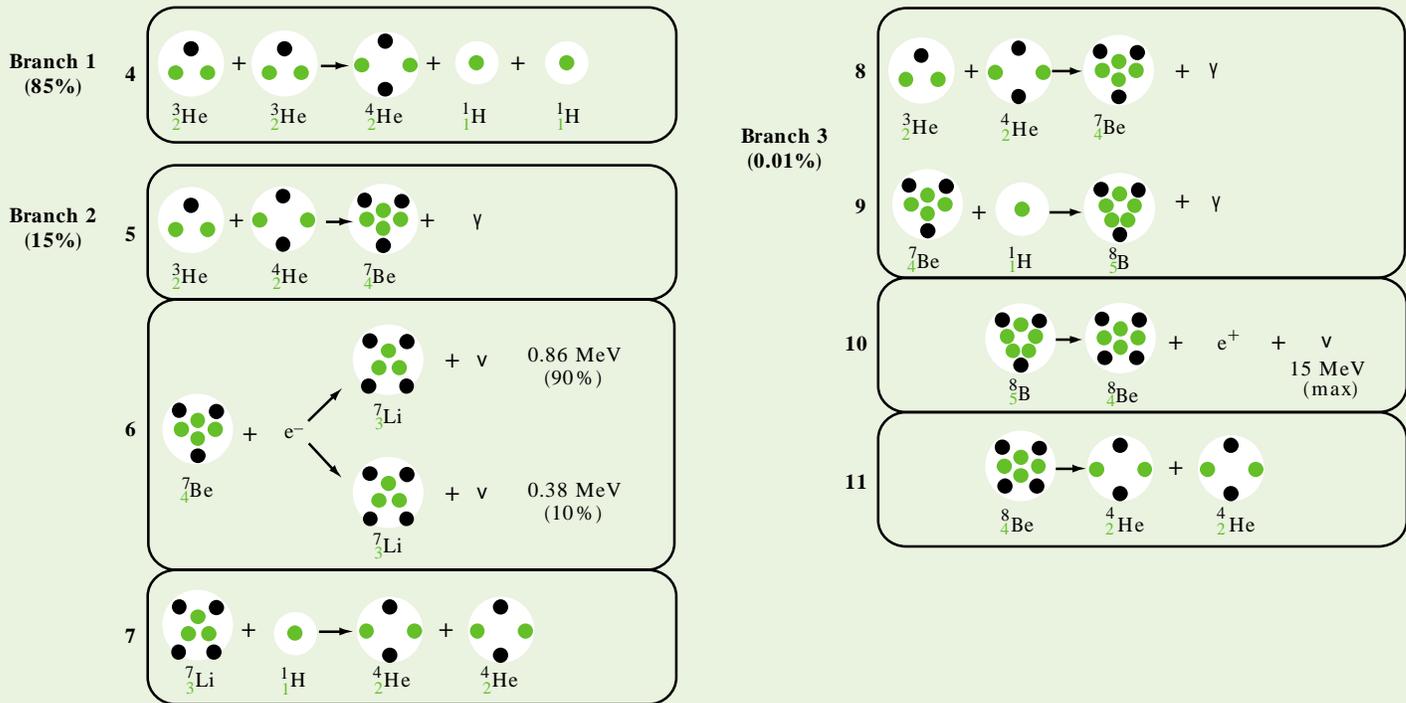
the so-called *pp* chain (see box above), builds helium out of hydrogen and is the dominant energy source in stars like the Sun and less massive stars. The second process is the CNO cycle considered by von Weizsäcker; it is most important in stars that are more massive than the Sun. Bethe estimated the 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

\*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.

his calculations led to a relation between the mass and luminosity of stars that was in agreement with astronomical observations.

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.

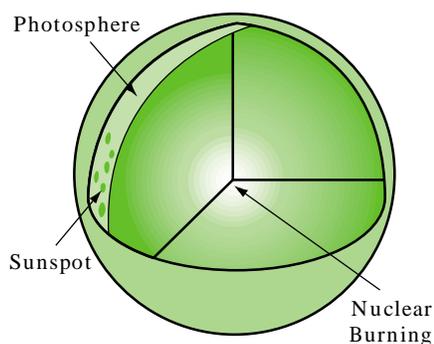
## DISCOVERY, CONFIRMATION, AND SURPRISE

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.’

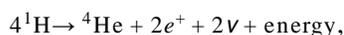
Is there any way to test the theory that the Sun shines because very deep in its interior hydrogen is burned into helium? At first thought, it seems impossible to make a direct test of the nuclear-burning hypothesis. Light takes tens of thousands of



*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



in which four hydrogen nuclei ( $^1\text{H}$ ) are fused into a single helium nucleus ( $^4\text{He}$ ) plus two positrons ( $e^+$ ) and two neutrinos ( $\nu$ ) 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 (Kamio-kande) 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  $\nu_e$ ) 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.



# What's Next in the Search for the Higgs?

by JOHN WOMERSLEY

*On March 1, 2001, Run II of the Tevatron Collider at Fermilab officially began. One of the primary goals of this project is to continue the search for the Higgs particle. What is this Higgs, why is it so important, and how will the Fermilab researchers try to ensnare it?*

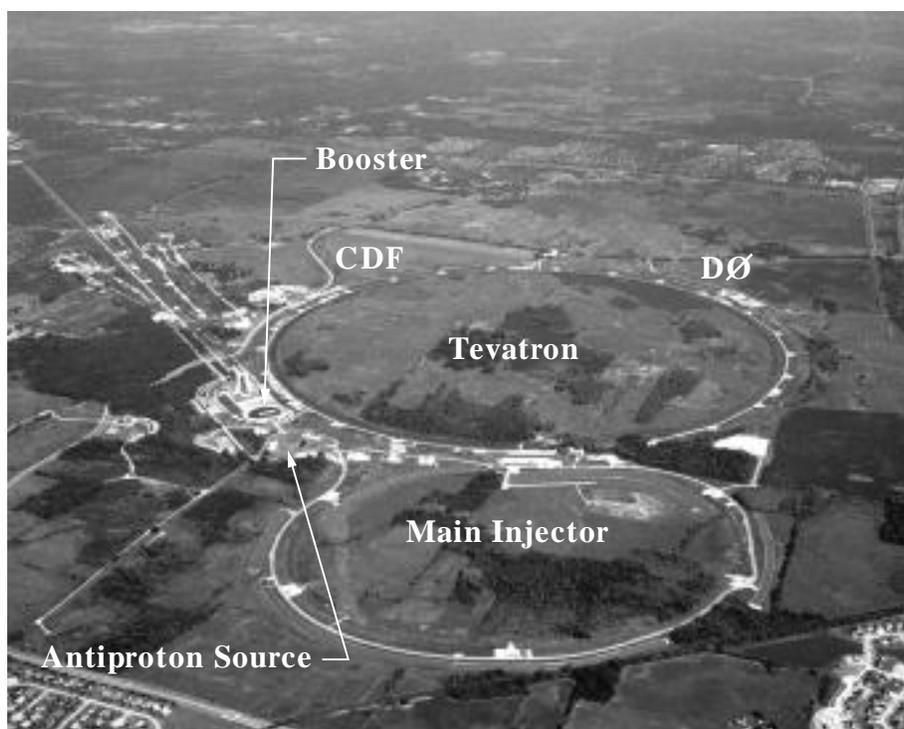
THROUGHOUT NOVEMBER and December 2000, the front pages of newspapers around the world were covered with stories about the American presidential election and the disputed vote count in Florida. While lawyers and judges argued about hanging chads and absentee ballots, an analogous story was unfolding in the science pages. Scientists and administrators at the European Laboratory for Particle Physics (CERN) were hotly debating whether experiments at the Large Electron Positron collider (LEP) had seen evidence of something called the Higgs boson. Normally sober scientific arguments turned heated, and petitions were even organized. In the end, the Director General of CERN decided to terminate operation of LEP in order to move ahead with construction of a new accelerator, the Large Hadron Collider (LHC). The LHC will certainly be capable of finding the Higgs, but it will not start doing physics until around 2007. Now that LEP is turned off, the focus of the action switches to Fermilab, just outside Chicago. Here the world's highest energy accelerator resumed data taking on March 1 and stands a good chance of clinching the discovery of the Higgs before the new European collider can start serious operations.

The Higgs boson has to do with mass. Mass is a fundamental property of matter. Through gravity—which is the only force important over astronomical distances—mass shapes the Universe. Mass is why you remain stuck to the face of the Earth and don't float off into space, and it's why the stars and planets and galaxies are the way they are. Despite Einstein's successes with general relativity, we still do not understand gravity in a quantum framework. But we believe we are getting closer to understanding the origin of mass itself.

In the cosmos, mass is present in (at least) two ways. There are atoms, the normal stuff that we (and the stars) are made of. In addition, there appears to be a lot of other stuff whose presence is felt through its gravitational pull but which cannot

be accounted for through visible stars and galaxies. This is called dark matter. For reasons to do with the amount of deuterium and helium that was produced in the very early Universe, physicists are pretty sure that most of this dark matter cannot be normal atoms. It has to be new particles of some kind. (This is the first of several connections that are going to appear between particle physics and the origin and structure of the Universe.) In contrast, the masses of the atoms arise largely through physics that is understood. A proton has a mass of 938 MeV, but is composed of three quarks that together weigh no more than 5 to 15 MeV (estimates vary). That means that more than 99 percent of the mass of a proton is due to the energy captured by the force holding it together (the so-called binding energy). This force, the strong force that acts on quarks, is called quantum chromodynamics (QCD), and it is a gauge theory, like electromagnetism. But unlike electromagnetism, the force carriers of the theory (called gluons) carry the QCD charge themselves, as if photons were electrically charged. This means that gluons interact with each other, that the QCD force becomes extremely strong for small momentum transfers, and that quarks therefore end up strongly confined into particles like the proton. Precise testable QCD calculations are available for high momentum transfer processes at particle accelerators and agree well with data. For soft processes like the binding of quarks into a proton, QCD can be calculated only numerically on a computer in what is called lattice gauge theory. Recent advances in computing

*Aerial view of the Fermilab site.  
(Courtesy Fermilab Visual Media Services)*

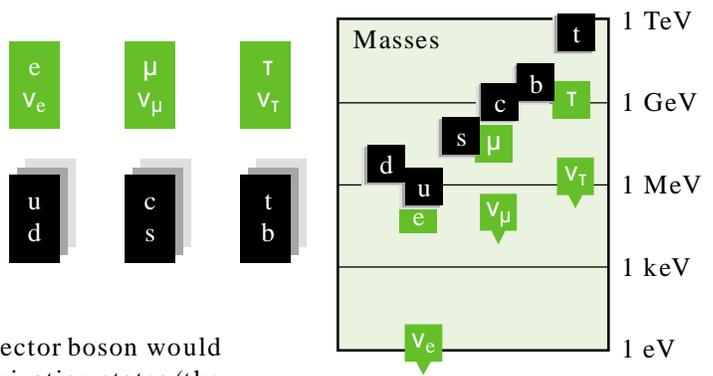


technology and calculational techniques have led to good predictions for the masses of bound states like protons.

So does this mean we understand mass? Yes and no. While 99 percent of the mass of the (visible) Universe is QCD, and we understand QCD, there is more going on. We should also aim to understand the masses of the elementary particles, like the electron, the neutrino, and the quarks. These particles come in three repeating generations, each one more massive than the last (while the up quarks in a proton have a mass of around 5 MeV, the charm quark mass is 1.35 GeV, and the top quark is a whopping 175 GeV). These patterns are not understood at all. Also, we should aim to explain the masses of the vector bosons which carry forces. While the familiar photon is exactly massless, the  $W$  and  $Z$  particles register 80 and 91 GeV; but all of them couple to matter in the same way. The large mass of the  $W$  and  $Z$  is what makes the weak force weak, and without it there would be no atoms and no you and me.

What does mass really mean, for an elementary particle? Leaving aside gravity for now, if a particle has mass, it travels through space more slowly than the speed of light. In fact, a simple way to think of it is that the particle interacts with the vacuum of space. The strength with which it couples to the vacuum is what we call its mass: it's a kind of stickiness. The top quark is just much stickier than the up quark. For force-carrying particles (vector bosons) like the photon there is an extra wrinkle. This is because the massless photon exists in two distinct polarization states,

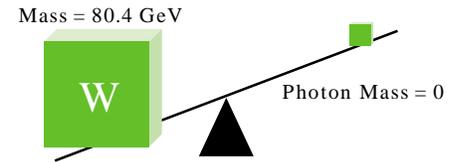
- Leptons
- Quarks



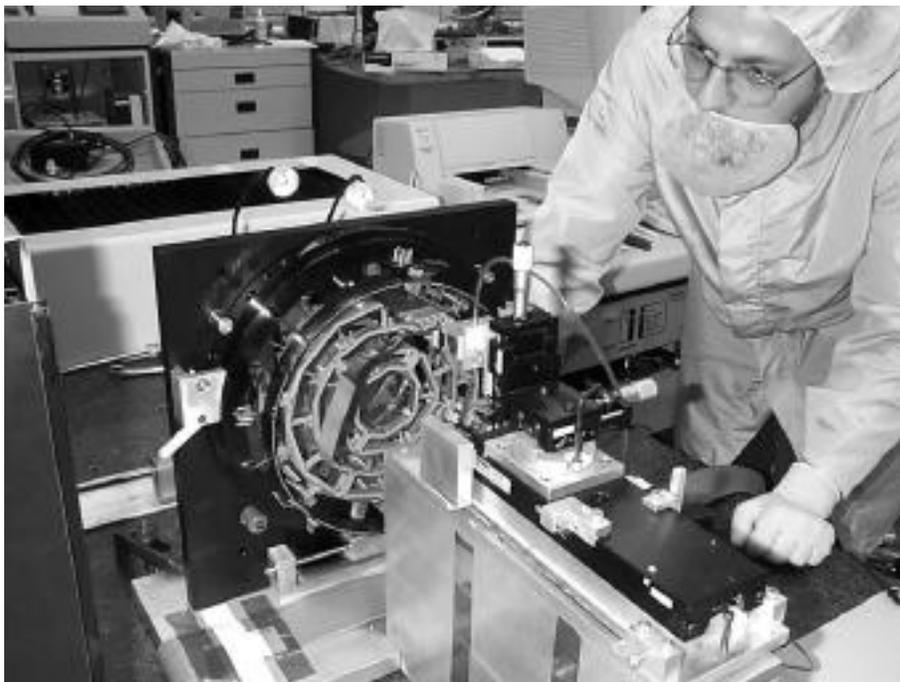
while a massive vector boson would exist in three polarization states (the extra longitudinal state only makes sense if the particle travels slower than the speed of light). So the transition from zero mass to an infinitesimally small mass is not a continuous one. This extra degree of freedom has to come from somewhere. One natural way to think of this is that the mass results from the two massless states somehow mixing with some other “thing,” and the three massive states that we see are the result.

This is exactly what is done in the Standard Model of elementary particle physics. The  $W$  and  $Z$  get their masses because they mix in this way with a field, called the “Higgs field,” that fills the Universe with a finite energy density. This can precisely account for the masses and coupling strengths of the  $W$  and  $Z$  and also the massless photon. If we additionally postulate that the same field interacts with all the electrons, neutrinos, quarks, and so on, then their couplings to it can account for their masses as well. This is a reasonably appealing picture, because it invokes just one new feature, the Higgs field, to explain the masses of both vector bosons and particles of matter. And it takes a rather metaphysical quantity like mass and casts it in

The three generations of fundamental particles, showing the patterns among their masses (Courtesy Particle Data Group)



The  $W$  boson is very massive, while the photon is massless. In the Standard Model, this occurs because the  $W$  interacts with a Higgs field that fills the Universe.



*The silicon detector for the DØ experiment under assembly at Fermilab's Silicon Detector Facility. (Courtesy Fermilab Visual Media Services)*

terms of something that physicists can understand and calculate: interactions between particles. Appealing, but is it correct? Well, it makes one clear and testable prediction: that there exists a neutral particle with zero spin (internal angular momentum) that is an excitation of the Higgs field. All its properties (production and decay rates, coupling strengths, etc.) are fixed, except its own mass. This predicted particle is the Higgs boson, and the highest priority of the worldwide high-energy physics program is to find it.

**O**VER THE LAST decade, the focus has been on experiments at the LEP electron-positron collider at CERN. Precision measurements of the properties of the  $W$  and  $Z$  bosons, together with Fermilab's top quark mass measurements, have set an upper limit on the

Higgs mass of around 200 GeV. At the same time, direct searches have excluded masses below 113 GeV. Over the summer and fall, data from LEP started to show some hints of a Higgs around 115 GeV, at the very limit of sensitivity; but the machine operations ended nonetheless. So until 2007, Fermilab has the playing field to itself.

The tool we shall use is called the Tevatron Collider. It is a three-mile circular particle accelerator about thirty miles west of Chicago. Inside this ring, protons and antiprotons are accelerated to high energies and brought into collision. The results of these collisions are studied by two giant arrays of instrumentation, the CDF and DØ detectors. The complex has an illustrious past as well as a big future: the bottom and top quarks and the tau neutrino were all discovered here. Since 1996 the accelerator has been turned off for major enhancements to the series of storage rings that feed into the Tevatron and also substantial upgrades to the detectors to boost the data collection rate and their capabilities. Operations resumed March 1, 2001. The first three years will deliver 20 times the sample that was already recorded; by the time the LHC starts running, this will have increased to a factor of 150. This huge increase in data is what will enable the detectors to see much rarer processes that would have escaped detection earlier—like the Higgs.

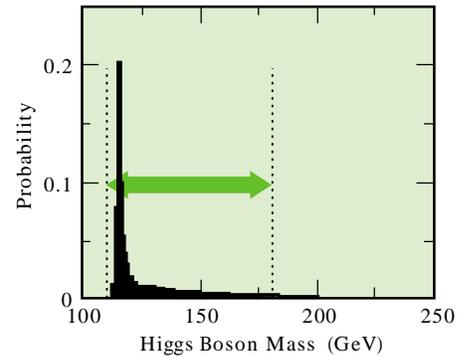
Each of the big detectors, CDF and DØ, contains a large array of sensitive elements surrounding the point in the Tevatron where the protons and antiprotons collide. These try to intercept, measure, and identify all the

products of the collisions. A key tool for the observation of a Higgs—a silicon vertex detector—is placed closest to the collision point, and both CDF and DØ have built elaborate new silicon detectors for the next run. Silicon detectors are basically big arrays of the same kind of silicon that’s inside integrated circuits. When a charged particle passes through, a little charge gets liberated in the silicon, and that can be detected and used to localize the particle track. The big advantage is that one can make very precise measurements of the track position, because the silicon can have very fine sensing electrode structures deposited on it by the standard integrated circuit techniques. Such precise measurements enable the tracks to be projected back to the proton-antiproton collision point with 10–15  $\mu\text{m}$  precision. This is sufficient to distinguish tracks that originated from the primary collision from those that were generated later, and especially those coming from the decays of  $B$ -mesons (unstable particles that decay after traveling a millimeter or so).  $B$ -mesons contain  $b$ -quarks and  $b$ -quarks are the most probable decay products of a Higgs with a mass up to about 150 GeV. With a good silicon detector, one can identify (“tag”) about half of all the high energy  $b$ -quarks while maintaining a false positive rate of half a percent.

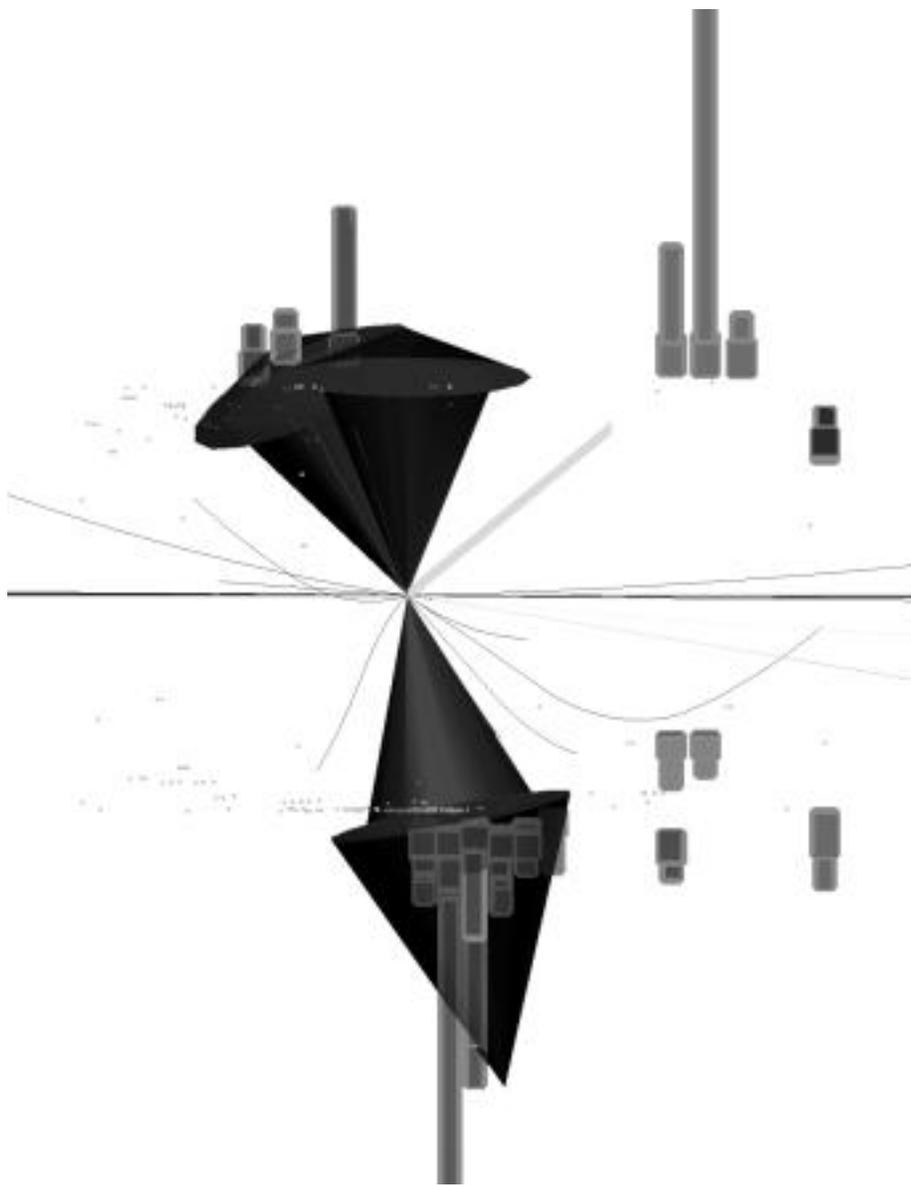
So how do we plan to use these tools to find the Higgs? As I mentioned earlier, if you assume a certain Higgs mass, then the production rate and decay properties are all fixed in the Standard Model. (Since the coupling strength of the Higgs to each particle equals that particle’s mass,

there is no freedom to adjust anything.) At the Tevatron, a 115-GeV Higgs (to choose a mass at random!) would be produced with a cross section about one fifth that of the top quark, resulting in maybe 1000 Higgs particles per experiment by the end of 2002. Alas, the dominant decay mode of these Higgs particles is to two  $b$ -quarks, and the signal would end up swamped by the huge background from the direct production of  $b$ -quarks. Thus the best bet appears to be to focus on a rarer process, one where the Higgs is produced together with a  $W$  or a  $Z$ . The production rate is a factor five less in this mode, but one has the distinct advantage that by focusing on the decays of the  $W$  or  $Z$  to electrons, muons, and neutrinos, one can select events of interest and get rid of a lot of the background. In fact, one can do this online as the data arrive, in the trigger system of the detector. That is an important consideration because proton-antiproton collisions are delivered at a rate of ten million per second and the detectors cannot write information from more than about fifty of those.

Even after selecting events with a  $W$  and a  $Z$  together with the two  $b$ -quarks from Higgs decay, substantial backgrounds remain and must be accounted for. For example, again at 115 GeV, we expect about 200 Higgs events after all the selection requirements, but these will be accompanied by nearly 1400 events from more “mundane” sources like top quarks and the direct production of  $W$ ’s and  $Z$ ’s together with  $b$  quarks. One key to finding the Higgs particle is to look at the invariant mass of the two  $b$ -quarks in the event: for the



*Probability distribution for the Higgs mass, taking into account indirect constraints and exclusion by direct searches. The arrow shows the approximate range that can be explored at the Tevatron. (Courtesy J. Erler, hep-ph/0010153)*



*Simulation of the tracks and energy deposits produced by a Higgs event at the Tevatron. This collision produced a Higgs, which decayed to two  $b$ -quarks (seen in the detector as energy deposits at 11 and 5 o'clock) and a  $W$  boson, whose decay products are an electron (track at 2 o'clock) and a neutrino (inferred from unbalanced momentum—the arrow at 12 o'clock). Discovery of the Higgs will require the accumulation and study of hundreds of events like this one.*

Higgs signal; this should show a peak at the Higgs mass, while the backgrounds will have no such structure. A lot of effort will be needed to optimize this mass resolution and to test that it behaves as expected, using the decay of the  $Z$  to two  $b$ -quarks as a calibration signal. Other key areas for success will be the performance of the  $b$ -tagging; electron and muon identification; and the indirect measurement of neutrinos through transverse momentum balancing in the detectors. All of these have to work well—and continue to work well as the beam intensity in the machine is increased to deliver enough Higgs-producing collisions. Of course, it

will take some time for operations to come up to speed. If the hints from LEP turn out to be incorrect, our studies imply that we will be able to say so by 2003. One or two years later we would be able to see a signal, and we expect a five standard deviation discovery at this mass by 2007. If we do see something, we will want to test whether it is really a Higgs particle by comparing its production rate with that expected, and by searching for its decays to particles other than  $b$ -quarks (for example,  $W$ 's and tau pairs). Since all of these rates are precisely fixed for a Higgs, any deviation from their expected values would tell us that we had caught a different kind of fish.

**T**HE STANDARD MODEL makes predictions that work at the level of one part in a thousand, and it would be completed by the observation of a Higgs particle. But rather than being the end of the road, many of us expect it to be the first window to a new domain of physics. This is because there are strong suggestions that the Higgs is not all we are missing. For one, the Higgs particle is unlike anything else in the Standard Model (there are no other elementary spin-zero particles). Another problem is that the mass of a Higgs itself would suffer very large perturbations from quantum effects and is mathematically very badly behaved (it ought naturally to be infinite, or at least close to that). The observation of a Higgs particle would explain how the particles got their masses, but it wouldn't explain why those masses have the values they do, or why there are three generations with a repeating pattern.

It is tempting then to imagine that the Standard Model is not complete and all-encompassing, but is merely an approximation (albeit a very good one at the energies we have explored). This happens naturally if it is part of a larger theory. Searching for hints of this larger theory will be a very important part of the Tevatron program. Theoretically by far the most attractive option for this larger theory is called supersymmetry (see “Is Supersymmetry the Next Layer of Structure?” by Michael Dine in the Winter 1999 *Beam Line*, Vol. 29, No. 3).

Just as every particle has a corresponding antiparticle, if the Universe is supersymmetric every particle also has a “superpartner” with the same properties except for a different value of spin (the particle’s internal angular momentum). Of course we know that the electron doesn’t have a spin-zero relative with the same mass—and neither do any of the known particles, so supersymmetry (if it exists) is a broken symmetry in the sense that the superpartners are much more massive than the normal particles. However, as long as these new particles aren’t way off scale in terms of mass—maybe in the range of a few hundred GeV—supersymmetry can make the Higgs much better behaved and solve some of the problems with the Standard Model. While closely approximating the Standard Model at low energies, a supersymmetric extension allows the electromagnetic, weak and strong forces to be unified at high energies and provides a path towards the unification of gravity as well. Viable quantum theories of gravity all seem to require

supersymmetry. All these nice features come at the cost of invoking a whole spectrum of new particles: multiple Higgs bosons (one of which looks very much like the Standard Model Higgs), strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos, and neutralinos. (The lightest of these new particles may well be stable, and if they were produced in the Big Bang the Universe would still be filled with them just like it is filled with the microwave background—which may be very relevant to dark matter.) So far, however, all searches for each and every one of these supersymmetric particles have proved negative. This failure to see anything allows us to set lower limits on their masses. And while we can’t be as precise as we can about the Higgs, physicists are starting to get the distinct feeling that at least some of these particles ought to be within reach of the Tevatron if supersymmetry is relevant for the Higgs.

Supersymmetry searches will therefore be an important part of the Tevatron program. They will be pursued on several fronts. First, the experiments will search for the strongly interacting squarks and gluinos, which are relatively copiously produced but decay hadronically and therefore suffer from large backgrounds. This is complemented by searches for the weakly interacting charginos and neutralinos (superpartners of the  $W$  and  $Z$ ) which have leptonic decays, some of which have very low Standard Model backgrounds (one very nice final state involves three electrons or muons). In addition, there are extra Higgs production mechanisms in super-

## SLEUTH



**A** LOT OF WHAT I have described here has used phrases like “theoretically the most popular model.” However, experimentalists—and I am one—are wary of implicitly assuming that theorists describe the Universe and experiments prove them right. We like to believe that the role of experiment is crucial, and we are just as likely to turn up something completely unexpected as we are to prove expectations correct. To make sure that we are not missing the completely unexpected, physicists in the  $D\bar{0}$  experiment have devised a new tool called “Sleuth” which is an attempt at a model-independent search for new physics. Sleuth doesn’t need to know anything about what you are searching for, it just needs the data events and a comprehensive set of the Standard Model processes that should account for them. Sleuth will then pick out the event or events that are least likely to arise from the Standard Model, and (this is the tricky part) quantify exactly what fraction of the time such results would be expected to arise by chance. Such an approach will never be as sensitive as a targeted search, because there are always special features to exploit if you know what you are looking for; but it has the great advantage that it is open to anything.  $D\bar{0}$  has carried out a systematic Sleuth study of 32 selected data samples from their 1992–1996 data, containing various combinations of electrons, muons,  $W$ ’s,  $Z$ ’s, photons, jets of hadrons, and so on. While a couple of these data sets have an excess of events over the expectation, Sleuth puts the overall agreement with the Standard Model at the 89 percent probability level. So we haven’t discovered anything yet—but recall that we are going to increase this data sample size by a factor of 150. Tools like Sleuth will be an important part of our armory.

symmetric extensions of the Standard Model that will give us additional ways to look for these particles. It is quite conceivable that the Tevatron experiments could discover supersymmetry before they find the Higgs.

At the beginning of this article, I mentioned that the connection between the particle physics of mass and gravity hasn't been made. Theoreticians had usually assumed that this connection would take place at extraordinarily high energies, of order  $10^{19}$  GeV, where the strength of gravity becomes comparable to that of the other forces. Recent revolutionary ideas have changed all that. The new concept is that while the quarks and leptons (us, in other words) remain trapped within the familiar three dimensions of space plus one of time, gravity may be free to propagate in a larger spacetime. This is pretty weird: hold up your finger, and imagine that every point on your finger extends some finite distance in an invisible dimension through which only gravity can travel. Weirder yet is the idea that such extra dimensions might be of macroscopic extent—as large as a millimeter. One consequence is that

gravity may become strong not at  $10^{19}$  GeV but at the 1 TeV scale that can be explored at Fermilab. The effects could be indirect and subtle, like a small deviation in the production rate of high energy electron pairs. They could also be direct and spectacular: high energy particles recoiling against what appears to be nothing at all, because their momentum is balanced by a graviton that has “escaped” into another dimension.

What I've described here is the work of many, many people. Each of the experiments is built and operated by collaborations of close to 500 physicists, of whom about 100 are graduate students pursuing degrees in high-energy physics. All of these physicists are working extremely hard right now to install and commission the detectors and the associated software. The Tevatron collider program in the next five years offers a real opportunity to advance significantly our understanding of the fundamental properties of matter. It is an exciting, challenging program that goes straight to the heart of the highest priority of high-energy physics worldwide.

## Further Information

For readers wishing to pursue this topic in greater detail, the following URLs will be helpful:

Fermilab  
<http://www.fnal.gov>

CDF Experiment  
<http://www-cdf.fnal.gov>

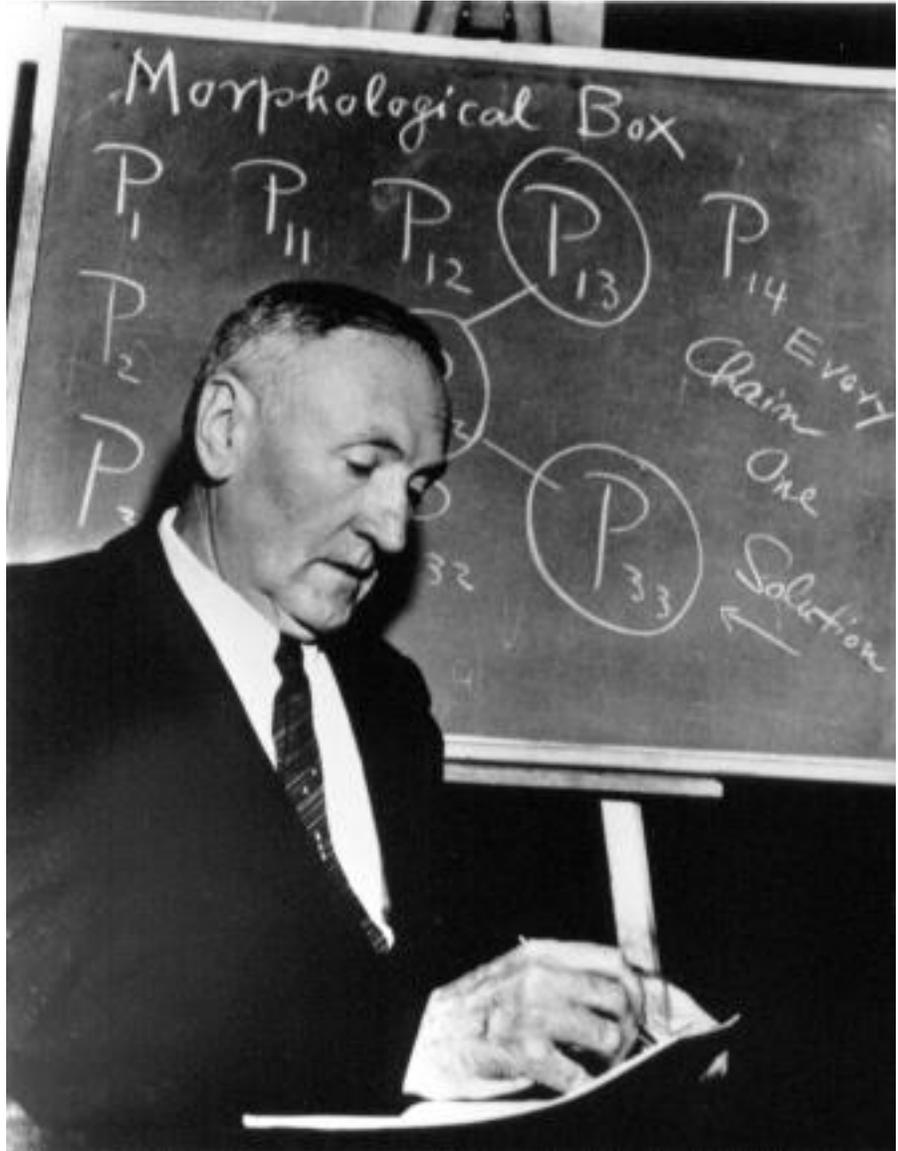
DØ Experiment:  
<http://www.d0.fnal.gov>



by STEPHEN M. MAURER

# IDEAMAN

*Sixty years ago,  
Fritz Zwicky  
was the only  
astronomer who  
thought that dark  
matter, neutron  
stars, and gravita-  
tional lenses  
were worth  
worrying about.*



Astronomical Society of the Pacific

**W**HEN FRITZ ZWICKY DIED IN 1974, he was remembered as a gifted observational astronomer who had discovered more supernovae than everyone else in human history combined. Today, Zwicky's reputation is bigger than ever, except that now astronomers think of him as a theorist. When researchers talk about neutron stars, dark matter, and gravitational lenses, they all start the same way: Zwicky noticed this problem in the 1930s. Back then, nobody listened . . .”

Fritz Zwicky was born in Bulgaria in 1898 but went to live with his grandparents in Switzerland at age six. In 1916, he enrolled in Zurich's Swiss Federal Institute of Technology to study mathematics, engineering, and physics. With World War I raging, Switzerland provided a haven for many of Europe's greatest minds. Zwicky met Albert Einstein, Wolfgang Pauli, and Vladimir Lenin. After graduation, Zwicky stayed on to pursue a degree in theoretical physics. His thesis applied the new science of quantum mechanics to crystals. He received his doctorate in 1922.

In 1925, the Rockefeller Foundation eager to bring quantum mechanics to the United States—gave Zwicky a fellowship. A lifelong skier and mountain climber, Zwicky asked the Foundation to send him where there are mountains. Trying to comply, the Foundation sent him to the California Institute of Technology. Zwicky grumbled that Pasadena only had foothills. Nevertheless, Caltech was a happy choice. At nearby Mt. Wilson, Edwin Hubble was working on his famous redshift relation. Zwicky began thinking about astronomy. When his fellowship ended, Caltech hired Zwicky as a professor.

**Z**WICKY BEGAN collaborating with a fellow German-speaker named Walter Baade in 1931. Astronomers knew that certain stars flared abruptly from time to time. Although most of these novae were close to the Earth, Baade noticed that a few old records described novae inside galaxies. During the 1920s, astronomers at Mt. Wilson had shown that galaxies

were immensely distant. In order to be seen at all, Baade and Zwicky realized that these super-novae had to be enormously bright (100 million times brighter than the Sun). They announced their discovery at an American Physical Society meeting in late 1933.

Not content with this empirical result, Baade and Zwicky added two key theoretical insights. First, they connected supernovae to the mysterious high altitude particles known as cosmic rays. Unfortunately, their evidence—which was limited to the surprisingly good agreement in energy between the two phenomena—remained circumstantial. Although Zwicky spent much of the 1930s trying to explain how particles heated inside an exploding supernova could escape into space, he admitted that his results fell well short of what was needed. The correct answer was found in 1949, when Enrico Fermi realized that shock waves hitting interstellar gas could produce cosmic rays outside the supernova itself.

Second, Baade and Zwicky tried to explain how such titanic explosions could occur at all. Then as now, any reasonable theory had to involve gravitational collapse. However, a simple calculation showed that the collapsing progenitor star had to free-fall over enormous distances in order to liberate enough energy. Unless the supernova remnant was unbelievably small (and dense) the process would stop too soon. By the early 1930s, quantum calculations had shown that the required densities could not be met by any form of matter that contained electrons.

The breakthrough came when English physicist James Chadwick

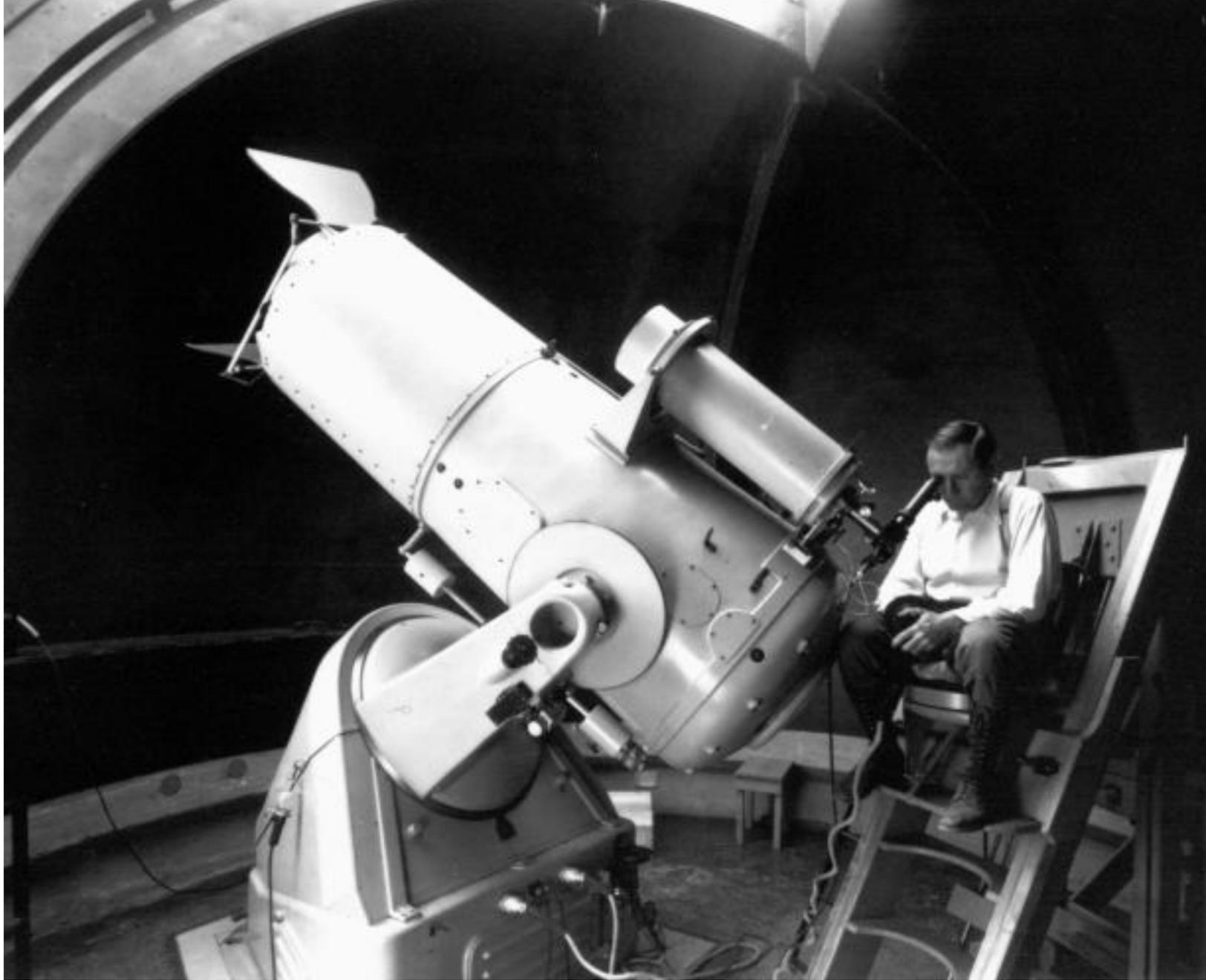
*Previous page: Fritz Zwicky invented a technique called morphology in order to think more efficiently. He is pictured here in the 1950s doing just that. Opposite: Fritz Zwicky at the Mt. Wilson 24-in. telescope in approximately the late 1930s. (Courtesy of the Archives, California Institute of Technology)*

discovered the neutron in 1932. Suppose that the star's electrons and protons could be turned into neutrons? "With all reserve," Baade and Zwicky wrote in March 1934,

"...we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the gravitational packing energy in a cold neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such."

Zwicky spent the next forty years pointing out that this comment had checked out in all essential aspects. However, it was largely ignored until Robert Oppenheimer and George Volkoff worked out the detailed physics of stellar collapse in 1939 without mentioning Zwicky's research. Even then, final confirmation had to wait until radio astronomers discovered the extraordinarily dense objects called pulsars in 1967.

**I**N ORDER TO LEARN more, Baade and Zwicky had to discover new supernovae. However, the chance of finding a supernova in any given galaxy was small, and conventional telescopes could only examine a few galaxies at a time. Fortunately, Baade had heard of a special telescope that could capture huge numbers of galaxies in a single, wide-angle photograph. Zwicky persuaded



Caltech to build an 18-inch Schmidt camera in 1936. Zwicky used this instrument for the rest of his life, finding 129 supernovae in all. Beyond their intrinsic interest, Zwicky believed that supernovae would eventually allow us to survey the universe to distances of billions of light years. That dream is only now coming true. (See *The Fate of the Universe* by Gerson Goldhaber and Judith Goldhaber in the Fall 1997 *Beam Line*, Vol. 27, No. 3.)

Zwicky's supernova search had an unexpected spinoff. Conventional telescopes had shown that a few

nearby galaxies were part of larger clusters. Now, Zwicky used the Schmidt to find new and more distant examples. These observations proved that clusters were the rule and not the exception.

**A**STRONOMERS HAD already measured velocities for most of the galaxies inside Zwicky's clusters. In 1937, Zwicky used astronomy's "virial theorem" to infer the clusters' masses from these data. (The virial theorem says that the total mass of a group of orbiting bodies can be

estimated from the velocity of its components. This is because, all else being equal, bodies in more massive systems must travel faster in order to resist the increased pull of gravity.) This led to a paradox. Based on data from the Milky Way, Zwicky should have been able to guess each cluster's mass from its observed brightness. This estimate turned out to be 500 times too small. Had Nature hidden the extra mass in a second, unseen component? Zwicky dubbed the substance "dark matter."

Most astronomers ignored Zwicky's result, much as Zwicky himself had

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dream is only now  
coming true.*

ignored an earlier paper by Johannes Kapetyn and Sir James Jeans on the ground that stellar motions inside the Milky Way were too complicated to interpret. Undaunted, Zwicky spent most of the next two decades conducting searches for previously overlooked gas and dust. In 1950, this dim object search uncovered starry bridges between galaxies, which Zwicky correctly attributed to near-collisions. Later searches found pygmy stars within the Milky Way and faint blue stars that were actually distant galaxies. Today we know that the latter objects are closely related to quasars.

Beginning in 1974, cosmologists began to rediscover the arguments for dark matter. Today, it is one of astronomy’s hottest research topics.

**T**HE IDEA that massive bodies can act as lenses goes back to the eighteenth century and received its most famous formulation in Albert Einstein’s 1916 General Theory of Relativity. In 1935, a Czechoslovakian engineer named R. W. Mandl wrote to Einstein suggesting that nearby stars could act as gravitational lenses by bending light from more distant objects. (The physicist Oliver Lodge had made a similar suggestion in 1919.) Initially intrigued, Einstein soon became discouraged after calculating that the lensed image would almost certainly be overwhelmed by glare from the foreground star.

Meanwhile, word of Mandl’s ideas had reached Zwicky. Zwicky realized that foreground glare could be overcome if searchers used galaxies instead of stars. In 1937, Zwicky published three articles predicting

that lensed galaxies would not only be amplified, but also bent into a distinctive ring. For the rest of his life, Zwicky begged astronomers to search for lensed galaxies. Finding even one lens, he insisted, could test general relativity; deliver light from unprecedented distances; and give astronomers a new way to detect dark matter. These are the same reasons that astronomers give for studying lensed galaxies today.

Zwicky was so confident of his prediction that he sometimes wondered why lensing hadn’t been noticed already. In fact, the first gravitational lens was found five years after Zwicky’s death.

**Z**WICKY WAS NEVER shy about describing himself as a romantic figure out of the Renaissance or lone wolf genius.

In fact, he invented a technique (morphology) which supposedly allowed practically anyone to think one hundred times more efficiently. Zwicky credited the technique for most of his insights.

Naturally to hear Zwicky tell it genius was persecuted. Friends say that Zwicky could explain his ideas patiently and was given to boisterous laughter. This did not stop him from railing against astronomy’s self-interested cliques and high priests. One of his favorite jokes was to call enemies “spherical bastards” (spherical, he explained, because they still looked like bastards from every possible angle). Zwicky even convinced himself that Baade had stolen his ideas. The famously gentle Baade was afraid that Zwicky might try to kill him.

**D**URING WORLD WAR II, the U.S. Army needed rockets to get heavily-loaded bombers airborne. Caltech aerodynamicist Theodore von Karman founded a corporation called Aerojet and won the contract. In 1943, Aerojet asked Zwicky to run its research department. At War’s end, Zwicky toured secret weapons programs in Germany and Japan. Later, he helped Aerojet develop many of the high-energy fuels used in today’s solid rocket boosters.

Corporate life did not improve Zwicky’s people skills. Once, Zwicky met a visiting delegation (including two admirals) at the plant gate and ordered them to leave. To hear Zwicky tell it, they were a bunch of unqualified civilians who had somehow wangled commissions. Aerojet old-timers also claim that Zwicky liked to win arguments with his fits. But he was a small guy, they usually add, so it wasn’t hard to pull him off.”

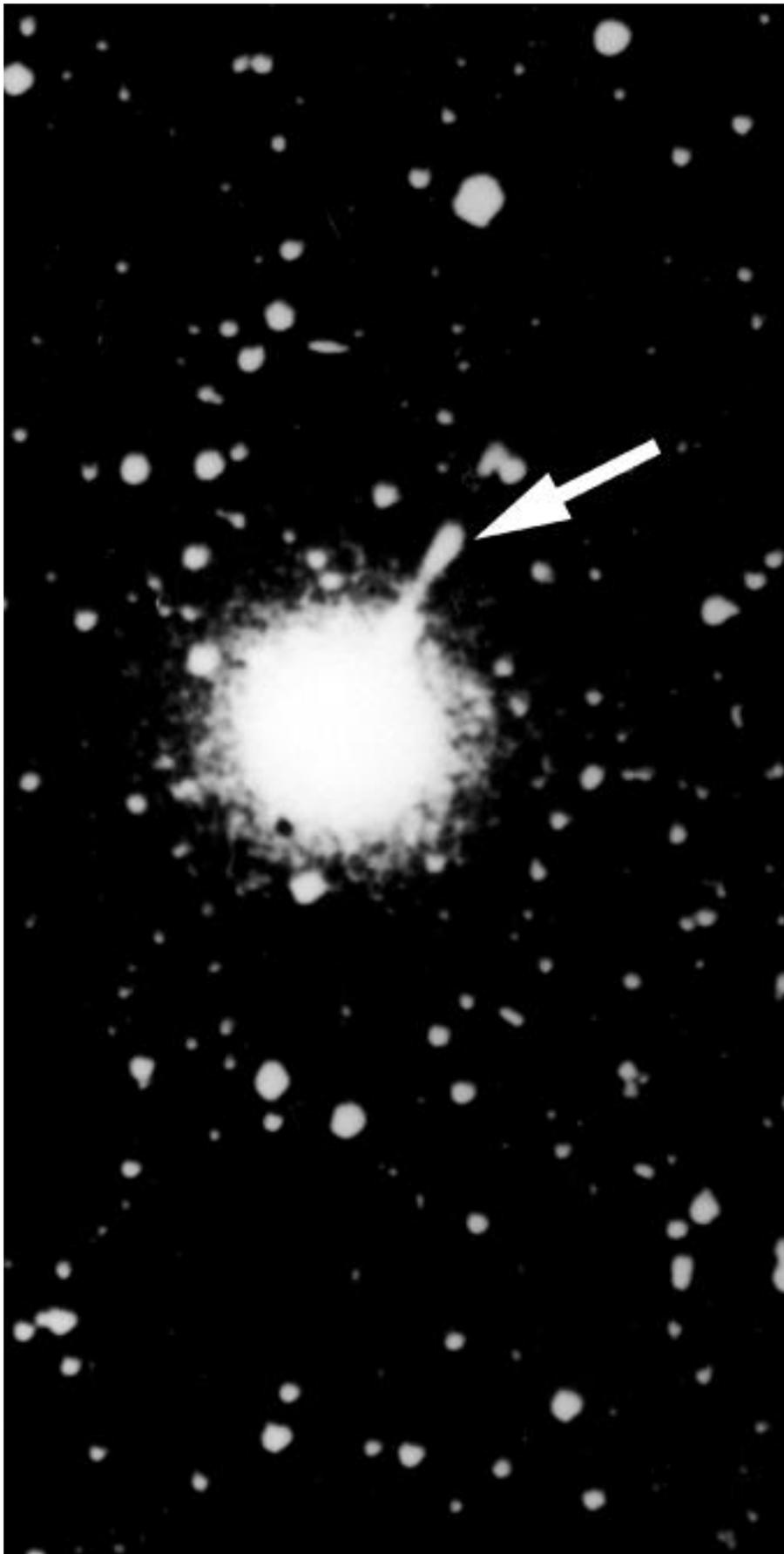
During the Second World War, the government gave Zwicky a security

clearance even though he had never taken out American citizenship. In 1955, the exception was revoked. Zwicky, who was intensely proud of being Swiss, decided to leave Aerojet rather than change his nationality. Besides, he told people, the U.S. Constitution does not allow naturalized Americans to become president. Why accept "second-class citizenship?"

**S**HORTLY AFTER THE War, Zwicky used his Aerojet connections to place an experiment aboard a captured V-2 rocket. Zwicky wanted to use shaped charges similar to the explosives used in Army bazookas to generate jets of liquid metal traveling at up to seven miles per second. Earthbound observatories could then photograph these "artificial meteors" to learn about natural meteors, atmospheric structure, and orbital reentry physics. Later experiments would have been more ambitious. Zwicky wanted to study flash and dust on the Moon and even return samples to Earth. Data from artificial meteor experiments also would have helped the U.S. to track shock waves from airplanes flying over Siberia. In 1999, the U.S. revived Zwicky's idea by crashing its Clementine satellite into the Moon. Earthbound observatories searched for water vapor, but saw none.

*The Aerobee was America's first rocket to probe outer space. Here, a launch in the mid-1950s is shown, similar to the one that detonated Fritz Zwicky's explosives above the New Mexican desert. (Courtesy Aerojet, Sacramento, California)*





*In 1957, Fritz Zwicky used high explosives atop an Aerobee rocket to blast jets of metal into space. Tracking cameras proved that at least one jet escaped Earth (arrow) and became the first man-made object to achieve its own independent orbit around the Sun. (Courtesy AP/Wide World Photos)*

Zwicky's V-2 flew on December 18, 1946. The *New York Times* called the experiment "a symbolic milestone in man's exploration of the universe" which might "open the secrets of travel between the planets." But while the rocket behaved flawlessly, observatories and amateur astronomers saw nothing. Zwicky believed that the charges had fizzled and asked for a second chance.

The Army said "no" and went on saying "no" until Sputnik was launched in 1957. Twelve days later, an Aerojet Aerobee rocket detonated three shaped charges 54 miles above the New Mexican desert. (This time, Zwicky installed the explosives himself.) Three jets were observed as far away as Mt. Palomar. Tracking cameras confirmed that at least one centimeter-sized projectile had become the first man-made object to escape the Earth and enter a separate orbit around the Sun.

**Z**WICKY HAD criticized President Harry Truman for dropping the atomic bomb on Japan. Now he brooded "that scientists' inventions have gotten completely out of hand." "I myself," Zwicky said, "can think of a dozen ways to annihilate all living persons within one hour." Zwicky even claimed (mistakenly) that future weapons or misguided fusion experiments could reduce the Earth to a miniature neutron star.

Zwicky's dreams were usually less gloomy. During the war, Zwicky had patented an air-breathing pulse jet "similar to Germany's V-1 buzz bomb. Why stop there? By the late 1940s, Aerojet was testing a

hydropulse"engine that burned" water (using sodium fuel) to make steam. And if water could burn, why not rock? Zwicky dreamed of the day when "terrajets" would burn minerals (using fluorine) in order to spit out jets of lava and gas. Zwicky claimed that the technology could dig tunnels and colonize the planets. Military versions could attack straight through the earth.

Terrajets were only the start. Eventually, atomic power could hollow out the moon, give it an atmosphere, or even move it elsewhere. And if mankind needed living space—for example, to separate its warring ideologies—the giant planets could be shattered into convenient, earth-sized pieces. Finally, future engineers could fire particle beams at the Sun to create a fusion-powered hot spot. This would generate enough thrust to move the whole solar system to Alpha Centauri in just 2,500 years.

**FRITZ ZWICKY HATED** the idea that galaxies were rushing apart because it implied a starting point, that is, that the Universe was young. He therefore called Hubble's redshifts "indicative" or "symbolic."\* But if the Universe was not expanding, why was distant

*\*In 1939, Zwicky "proved" that the Universe had to be much older than Hubble's law implied. Many clusters, he argued, were beautifully spherical. But the laws of physics said that an initially chaotic group of galaxies could only become symmetrical through a series of close encounters among three or more galaxies. Since such encounters were fantastically rare, the Universe had to be at least  $10^{18}$  years old.*

light redshifted? Zwicky offered three answers. First, Einstein's laws implied that photons passing a star would first gain and then lose energy. Zwicky argued that the first effect was slightly larger, producing "gravitational drag." Second, small overlooked terms in Maxwell's equations and quantum mechanics might allow light to become "fired" after billions of years. Finally, the physical laws themselves might have changed: Why shouldn't light emitted billions of years ago be redder than it is today?

Strangely, the man who had shown that most galaxies reside in clusters refused to admit that "super clusters" (clusters of clusters) existed. This led to a series of acrimonious debates with astronomer George Abell during the 1950s. Zwicky even claimed that the absence of superclusters showed that gravity stopped working beyond 60 million light years or so thereby invalidating General Relativity and the Big Bang. According to Zwicky, a "graviton" weighing  $10^{-64}$  grams "explained" the effect quite nicely.

Finally, Zwicky concocted a wild theory in which chunks of neutron matter ("goblins") orbited deep inside massive stars. Goblins were ordinarily invulnerable, since a 10-meter ( $10^{29}$  ton) object would cut through the star like tissue paper. Occasionally, however, a close encounter between two goblins would boost one of them to a higher orbit. No longer stabilized by the star's high pressure core, the unlucky goblin would explode producing flare stars and gamma-ray bursts.

**BELIEVING** that educated people owe a debt to society, Zwicky organized a program after World War II that collected and shipped 15 tons of scientific journals to war-damaged libraries around the world. He also directed an organization that supported orphanages.

Charity reinforced Zwicky's contempt for the "inhuman and idiotic treatment" of native peoples under colonialism. "We are not likely to succeed in unifying the world," he warned, "as long as the Americans and the British, or for that matter any other people, feel and act as if they are better and superior to all others."

**ZWICKY BECAME** professor emeritus in 1968. Thereafter, he traveled extensively and opened a second home near Berne, Switzerland. Friends thought that he wanted to become a member of the Swiss Parliament. He died six days before his seventy-sixth birthday, on February 8, 1974. He was buried in Switzerland.

Zwicky often joked that he wanted to live to be 102, since hardly anyone gets to live in three centuries. He would have enjoyed his current reputation. In the final analysis, though, Zwicky probably didn't care whether people believed his ideas or not. Zwicky knew. That was enough.



# THE UNIVERSE AT LARGE

## *Astrophysics Faces the Millennium IV* Stellar, Stellar Bang Bang

by VIRGINIA TRIMBLE

*What never? No,  
never! What never?  
Well, hardly ever.*

Captain Corcoran and  
Chorus in HMS Pinafore,  
W. S. Gilbert

You would have to wait  $2 \times 10^{18}$  years for the sun to suffer even a glancing collision with another star in its present environment. Unfortunately, the total solar lifespan is only  $10^{10}$  years, and even the environment is probably not good for much more than  $10^{11}$  years. This is not a new discovery and has been remarked upon (typically with some sarcasm) over the past century, any time anybody has suggested stellar collisions as a mechanism for anything, whether planet formation, supernova explosions, or quasars.

Nevertheless, in recent years, stellar collisions and mergers have come to be taken seriously as part of the physics of the evolution of binary stars, clusters, and galactic nuclei. A modern estimate is that there is a collision every hour somewhere in the observable universe, though (as the resort T-shirts say) all we get may be some massive blue stragglers and a funny planetary nebula. Whether this is on the whole good or bad depends on your point of view, and both opinions go back at least two hundred years.

### FEW OR MANY?

William Herschel, after resolving a good many nebulae into star clusters in the late eighteenth century, worried that the shock of one star's falling upon another would lead to general destruction, but concluded that the great Author has

amply provided for the preservation of the whole”and that “the destruction of now and then a star in some thousands of ages [is] perhaps the very means by which the whole is preserved and renewed.”

Even earlier, at a time when comets, stars, and shooting stars were by no means so distinct as they now seem, G. L. Leclerc, Comte de Buffon (1707–1788) went on record with the idea that the planets might consist of material splashed out of the Sun by a comet impact. Just for the record, comets do actually hit the Sun, though the results, first spotted by the Solwind satellite in 1979 and soon after by the Solar Maximum Mission, are a good deal less dire (except for the comet) than Buffon envisaged.

Laplace’s 1796 “nebular hypothesis” for the origin of the planets was then more popular for a century or so, but the dawn of the twentieth century saw Thomas C. Chamberlin (also an active participant in the “age of the Earth” debate) and Forest Ray Moulton of the University of Chicago declaring that the nebular picture could not account for the fact that most of the angular momentum of the solar system resides in planetary orbits and only a few percent in the Sun. They advanced tidal encounters as an alternative.

Sir James Jeans and Sir Harold Jeffreys revisited the tidal idea in the interwar years, with Jeans, at least, explicitly acknowledging that planetary systems must, under this hypothesis, be very rare, accompanying at most one star in  $10^5$ , even after the  $10^{12}$  years that he claimed for the age of the galaxy and Universe.\* Curiously, in a 1942 *Nature* paper not long before his



ASP/ Yerkes Observatory

Sir James Jeans

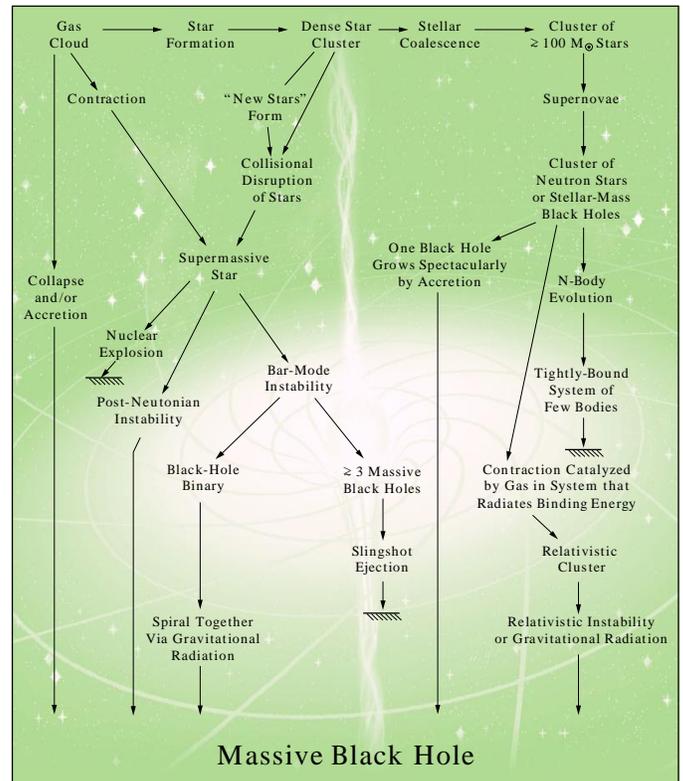
\* How Jeans got  $10^{12}$  years where we now find  $10^{10}$  is a somewhat related story, too long to tell here, which involves tidal interactions of stars in clusters, galaxies, and binary systems.

death, Jeans managed to bump his estimate up to one star in six, by allowing for interactions while the stars were forming and much more extended than our Sun is now.

The last gasp at a stellar encounter model for formation of the solar system came from Raymond Arthur Lyttleton in the early 1950s, even as fashion was swinging back to the nebular scenario. His version involved three stars, an initial close binary and an intruder, with the potential for star exchange as well as planetary extrusion. Perhaps not by chance, Jeffreys and Lyttleton appear also to have been the last practicing geophysicists to deny firmly the existence of mantle convection and plate tectonics in the earth.

### SUPERNOVAE AND QUASARS

In 1933–1934, Walter Baade and Fritz Zwicky drew the first clean cut between common novae and super-novae (though the word, also with hyphen, appears in a 1932 paper by Knut Lundmark). They also suggested a correct energy source, collapse of a normal star to a neutron star. The idea has a precursor in the 1931 suggestion by E. A. Milne that novae might represent the collapse of ordinary stars to white dwarfs. The stellar collision model for supernovae came from Fred Whipple in 1939 (yes, the same Whipple you associate with the dirty iceberg model of comets, on which he is still working). This mechanism also had a precursor, in the form of novae as stars being hit by planets or asteroids, put forward by William S. Pickering, H. von Seeliger, and others in the 1920s. Pickering, at least, had in mind that the intruder would penetrate deeply enough to release a burst of what was then called subatomic energy. This is actually more or less how modern novae work, though the intrusion is by diffuse gas accreted over the whole star surface not by a compact object (and the star has to be a white dwarf). Whipple made use only of the kinetic energy of the collision of fast moving galaxies in galactic nuclei. Thus his suggestion is at most a very distant prequel of our current understanding of another sort of supernova (called Type Ia), which may arise



Possible evolutionary paths for a large gas cloud at the center of a galaxy. A number of intermediate processes involve stellar collisions and mergers, but the end product is nearly always a massive black hole, and this is currently regarded as the most likely central engine for quasars and other galaxies with active nuclei. The scheme is that of Martin Rees (in his 1978 Halley lecture); the drawing is in the hand of Roger Griffith, then one of the editors of *Observatory* magazine and is reproduced with their permission.

when two white dwarfs spiral together, collide, and release oodles of “subatomic energy,” completely disrupting the star(s) involved.

Quasars and other active galactic nuclei are even more vigorous blow-offs than supernovae. The 1954 identification of the radio source Cygnus A with what, at first sight, appeared to be two galaxies in collision, inspired, if not quite a thousand theoretical flowers to bloom,

at least a few dozen, many of them (including stellar collisions, but also multiple supernovae and infall of gas into a galactic nucleus) in the garden tended by Iosef S. Shklovsky. The weeding-out process was far from complete in 1963, when the discovery of the first two quasi-stellar radio sources (QSRs, later quasars) added considerable fertilizer to the problem.

The first to say “stellar collisions” in this context were Thomas Gold, Ian Axford, and E. C. Roy in the *Proceedings* of the December 1963 meeting that we now think of as the First Texas Symposium, and Lodewijk Woltjer in *Nature*. Perhaps the most prescient aspect of the Woltjer paper is that it is followed on the same page by a comment from Fred Hoyle, pointing out that the requisite crowded system of stars will inevitably evolve to some sort of supermassive object via a succession of stellar collisions and mergers. Hoyle and William Fowler had thought of such an object as an engine for radio galaxies just before quasars were added to the mix.

The required succession of collisions and mergers can be a remarkably complicated one (see figure on the opposite page), but no matter which path you follow, eventually you end up with, or in, a black hole. Martin Rees, who sketched the original figure, said that, if you were going to end up with a black hole anyhow, you might as well start your model with one, and indeed quasars (etc.) powered by a succession of supernovae (perhaps collisionally triggered) or other sums of many little things have gradually gone out of fashion, strongly aided by observations of luminosity fluctuations containing more energy than a stellar rest mass, jets that preserve directionality for a million years or more, and so forth.

### SCAM RISES AGAIN

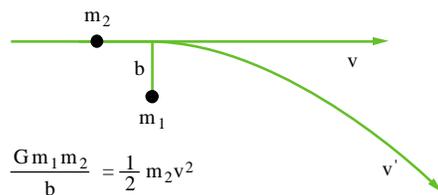
Stellar Collisions And Mergers leads to a perhaps unfortunate acronym for a process you are expected to take seriously, but into every life a little RAIN (Random And Inconvenient Noise) must fall. You can estimate the rate of occurrence of collisions and mergers in any context that interests you by remembering that

$$1/t = n \sigma v,$$

where  $t$  is the average waiting time for one particle to experience an encounter;  $n$  is the number density of particles;  $\sigma$  is the cross-sectional area of a typical particle; and  $v$  is the average relative velocity. While  $1/t$  is always small for any one star (except in binary systems), the aggregate for a star system can be many collisions over its lifetime.

Obviously collisions become more likely if  $n$  is large (crowded conditions). This favors the centers of the dense star clusters found in galactic halos (called globular clusters) and centers of galaxies, where  $n$  can exceed our local value (0.1 stars per cubic parsec) by factors of a million and more. Large  $\sigma$  (big particles) should also enhance the rate. But there is a catch. Stars are large as they are forming and again late in their lives when they become red giants or supergiants. Neither phase, however, lasts very long, so that the total number of collisions is not much larger than for normal, solar-sized stars. Close encounters in crowded environments may, however, lead to red giants stripping each others’ extended envelopes or to protostars capturing each other into bound orbits or merging when they are young.

Finally, you might reasonably conclude that large velocities are a good thing, as is indeed the case if you are talking about nuclear reaction rates. But in the stellar case, the effective size of a star is often not its geometrical radius but a sort of impact parameter at which



*The effective cross section for stellar interactions is often that defined by an impact parameter,  $b$ , such that the kinetic energy of the passing particle is equal to its gravitational potential relative to the other particle and its path is significantly perturbed. This can be much larger than the geometric cross section. Since  $b$  scales as  $1/v^2$ , the collision rate ends up with  $v^3$  in the denominator.*

gravitational potential and kinetic energies are equal. This leads to a collision rate ( $1/t$ ) with  $v^3$  in the denominator, so that slow and steady wins the race. Two isolated stars with zero initial velocity must eventually fall together, even if they start out very far apart. This was the point that worried Herschel.

Thus a twenty-first century astronomer in search either of observations that might be explained by SCAMs or of likely scenarios to calculate and predict something from will head for (a) galactic nuclei, (b) star clusters (either dense old ones, or less dense ones where star formation is still in progress), or (c) gravitationally bound pairs of stars (binaries), whose effective stellar density can be as large as  $10^{10}$  stars per cubic parsec, and which will inevitably collide or merge if angular momentum is removed by magnetic stellar winds or gravitational radiation. Typical velocity dispersions are a few to a few tens of km/sec in the clusters and hundreds to thousands of km/sec in galactic nuclei.

Incidentally, the Universe as a whole is a totally useless site. Early on, when it was dense, there were no stars. In the distant future, if the Universe should recollapse (unlikely), rising radiation temperature will evaporate the stars long before they hit each other. Galaxies do collide, merge, and cannibalize each other—the Milky Way is currently nibbling on a small snack called the dwarf spheroidal in Sagittarius. But even when one galaxy smacks another face on, very few stars hit others. The process does, however, make a real mess of the gas in the galaxies, and we see the effects.

### WHAT ARE THEY GOOD FOR?

It is possible, at least for a rambler like the present author, to ramble on for pages about specific collision/merger sites and processes and the astronomical phenomena that probably result. (See the concluding paper in the conference proceedings advertised under “Further Reading.”) But, instead, here is a list of astronomical questions and problems to which some sort of SCAM may well be the answer. All are topics of current investigation,

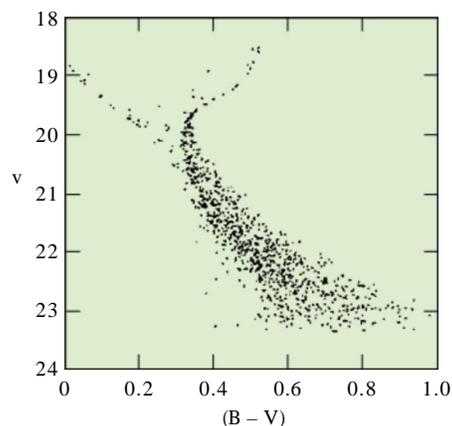
meaning that some astronomer earns his precarious living by writing papers and giving seminar talks about them:

1. How does Nature assemble stars exceeding 10 times the mass of the Sun, when continued accretion onto a core of  $10 M_{\odot}$  would release so much radiation that the gas gets blown back out?

2. What are the origins of very rapidly rotating giants (called FK Comae stars) if angular momentum is conserved as the stars expand from the main sequence?

3. What is responsible for the small set of stars that look younger than their host clusters or galaxies when there is no gas around to support ongoing star formation? They are called blue stragglers, SX Phe stars, and worse things, and are to be found in nearly all compact, old star clusters and in some less compact ones, in dwarf galaxies, and in the halo of the Milky Way. The stars call attention to themselves by being bluer and brighter than the vast majority of unevolved (single) stars that belong there.

*A plot of brightness vs. color (surface temperature) for the stars of the globular cluster NGC 5053. This almost looks like real data, but it is in fact a simulation that begins with a certain fraction of the cluster stars in binary systems and lets both single and binary stars evolve for*



*about 14 billion years. The stars are then subjected to typical amounts of observing error. The blue stragglers, produced by mass transfer and mergers in close binaries, are the ones with B-V less than 0.35 and V between 18.5 and 20.0, meaning that they are both too blue and too bright for single stars on the main sequence (the broad diagonal swath of stars upwards from lower right). Courtesy of the calculators, P. J. E. Leonard and G. G. Fahlman, Astrophysical Journal 102, 996 (1992).*

4. Who ordered that? Meaning not Rabi's muon but single, stray, odd stars, each of which is loved (and owned, at least as much as you can own a cat) by some practicing astronomer. They have names like V652 Her, WN8 stars, and the planetary nebula in M15 and are too massive for their surroundings.

5. Where do r-process isotopes (the ones made by rapid capture of neutrons onto seeds of iron-group elements) come from? In this case, at least one of the stars had better be a neutron star.

6. Given that Type Ia supernovae exist and are important (they're the ones used for cosmological distance measurements that suggest an accelerating universe), why haven't we found many promising progenitors?

7. Do we have a complete inventory of the things that can happen around massive black holes in quasars (etc.) to feed gulps of gas to the monster and cause flaring?

8. What makes gamma-ray bursters, now that we know they are things of  $10^{52\pm 1}$  ergs in distant galaxies not piddling surface explosions in our own? Just at the moment, the best-buy scenario has two answers: The collapse of a single, very massive star to a rapidly rotating black hole makes the events with long-lived X-ray, optical, and radio afterglows; and mergers of close neutron star pairs make those without such tails.

9. Even if Herschel was wrong to worry about stars all eventually being destroyed by collisions, what would an environment denser than ours do to (a) the stability of planetary orbits, and (b) the continued existence of a cloud of future comets (outside the orbit of Neptune) that can be perturbed down into the central solar system by passing stars? People who actually work on stellar dynamics don't take this one very seriously, but, in a brief "it's summer vacation" discussion. Gregory Benford and I concurred that the answer was a series of "good, bad, good, bad," in the following sense. Stars very far apart, as in our neighborhood, trigger only rare episodes of cometary impacts. A bit closer together and you get hit too often to recover in between. Still closer, the pre-comet (Oort) cloud is destroyed early and life evolves in peace (perhaps too much peace, with no recycling of

ecological niches?). Still closer and the planets themselves go truly wandering. Fold in the need for heavy elements to make terrestrial planets, and you can end up with a galaxy that is a patchwork of good and bad places to live!

The Earth seems to be one of the better ones and, in case I haven't mentioned it lately, the hard work and broad-mindedness of the editors of *Beam Line* is one of the many things that make it so.

#### SUGGESTIONS FOR FURTHER READING

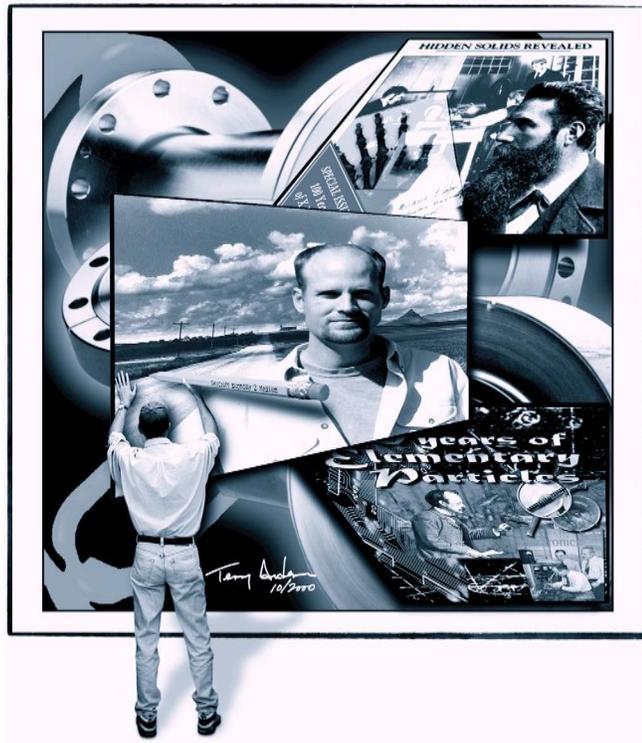
I have found a brand new historical volume to crib from! It is *The Book of the Cosmos: Imagining the Universe from Heraclitus to Hawking*, by Dennis R. Danielson of the University of British Columbia (Perseus Publishing, 2000). The contents include extracts from the writings of nearly 100 philosophers, scientists, poets, and popularizers from something BC to roughly now, plus introductions, bridges, and explanations from the author.

The proceedings of a May 2000 conference called "Stellar Collisions and Mergers" should appear sometime in 2001 in the Conference Series of the Astronomical Society of the Pacific, edited by Michael M. Shara.

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# CONTRIBUTORS

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For eleven years, **TERRY ANDERSON** of SLAC has been using his artistic imagination and skill to enhance the *Beam Line*. From designing the cover of the 4-color inaugural issue in 1990 to the present one, he has never missed a beat. Nor has he ever compromised his vision for improving the graphics. In his own words, written to one of the editors (RD) in 1998:

*It's not the software and it's not my ability that has made the quality of the graphics what they are today. It's Beam Line, the ongoing process of improving its looks. What we have now would not have been possible without the experience gained from previous years. I have had the freedom to try many things, some worked, others didn't, but we tried.*

Yes, Terry, you have tried—and succeeded—and our readers are the beneficiaries of your “can do” team spirit. You have taken technical material, reduced it to a basic level, and improved its clarity. You have shown us what dedication and a talented gentleman from Montana can do. We thank you.



**JOHN N. BAHCALL** received the Presidential Medal of Science in 1998 for his theoretical work on solar neutrinos and for his role in the development of the Hubble Space Telescope. Since 1971, he has been professor of Natural Science at the Institute for Advanced Study and has led an active postdoctoral and sabbatical program in astrophysics.

In 1994 he was awarded the Heinemann Prize for his work on solar neutrinos—a field which he and Ray Davis have worked to develop for much of the past 40 years. He is the author of the book **Neutrino Astrophysics**, a member of the National Academy of Sciences, and a past president of the American Astronomical Society.



**JOHN WOMERSLEY** is currently a tenured scientist at Fermilab. He obtained his doctorate at Oxford University, working on the EMC experiment at CERN. After this, he thought it would be interesting to spend a few years in America. Those few years turned into fifteen (so far) and have involved a postdoc for the University of Florida, a faculty position at Florida State, and work as a staff scientist at the SSC Laboratory, before moving to Fermilab in 1994. He has worked on calorimetry, simulation and reconstruction software, and physics analysis at hadron colliders. He was US Physics Coordinator for the CMS experiment and manager of the DØ offline reconstruction program before being elected co-spokesman of the DØ Experiment in 1999.



**STEPHEN M. MAURER** is a California attorney who has handled intellectual property and technology-related lawsuits since 1982. He earned his BA degree from Yale University and his JD degree from Harvard Law School. A lifelong amateur astronomer, Maurer first started collecting stories about Fritz Zwicky after talking to witnesses in a case involving historic rocket operations near Sacramento, California.

Maurer recently devoted a sabbatical year to taking advanced economics classes at UC Berkeley. He has spent most the past two years studying legislative proposals to commercialize scientific databases. Much of this work has appeared in *Science* and *Nature*. Maurer is currently collaborating with UC Berkeley economist Suzanne Scotchmer on a massive statistical study of how California judges decide cases.

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Author **VIRGINIA TRIMBLE** was married to Joseph Weber from March 1972 until his death on September 30, 2000. The picture was taken in the family kitchen a few days after their first, county-courthouse, wedding, by David Weber, then 16 (later “our son the doctor”), the youngest of Weber’s four sons by his first wife, who died in 1971. From 1973 onward, Weber and Trimble shared out their appointments, spending half of each year at the University of California, Irvine (where she is tenured) and the other half at the University of Maryland (where he was tenured until forcibly retired in 1989).



Physicists over 65 will remember Weber as the author of “Amplification of Microwave Radiation By a Substance Not in Thermal Equilibrium,” presented at the June 1952 IRE meeting in Ottawa, Canada, and published the next year in *Trans. IRE*.

Physicists between about 45 and 65 will probably recognize him as the inventor, builder, and operator of the first detectors for gravitational radiation. Physicists under 45 may well say, “Who?” In fact, however, at least one detector was in continuous operation from 1969 onward, “In case,” Weber used to say, “there is a supernova.” The Maryland antennas were indeed the only ones in the western hemisphere collecting data at the time of SN 1987A, along with one at Rome, and would almost certainly have been the only operating detectors for a 1990s event in the Milky Way. Correlations between signals recorded by the Maryland and Rome antennae and by several particle detectors (including IMB, Baksan, Mt. Blanc, and Kamioka) during SN 1987A were reported in a number of journals and conference proceedings, though largely unrecognized by the community.

From about 1985 onward, Weber focussed on the development of a coherent technique for neutrino detection, roughly analogous to Mossbauer scattering of gamma rays, though not to the exclusion of gravitational radiation. A paper in press as this is being written reports coincidences between antenna signals and X-ray emission from the bursting pulsar recorded by BATSE. The last data tape on the 38-inch bar detector rang out a few days after he died.

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## 2001 DATES TO REMEMBER

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- May 5–7 Workshop on Prospects for CLEO/CESR with  $3 < E_{\text{cm}} < 5$  GeV, Ithaca, New York (persis@mail.lns.cornell.edu or man5@cornell.edu; <http://www.lns.cornell.edu/public/CLEO/taucharm/>)
- May 6–19 CERN-CLAF School of Physics, Itacuruca, Brazil (Claire Earnshaw, CERN, 1211 Geneva 23, Switzerland or Claire.Earnshaw@cern.ch; <http://www.cern.ch/LatAmSchool/>)
- May 7–9 PHENO 2001 Symposium, Madison, Wisconsin (Linda Dolan at ldolan@pheno.physics.wisc.edu; <http://pheno.physics.wisc.edu/pheno01/home.html>)
- May 9–17 CERN Accelerator School: Particle Accelerators for Medicine and Industry, Pruhonic, Czech Republic (suzanne.von.wartburg@cern.ch; <http://cern.web.cern.ch/Schools/CAS>)
- May 21–Jun 1 Workshop on Physics at TeV Colliders, Les Houches, France (houches@lapp.in2p3.fr or secretariat.houches@uif-grenoble.fr)
- Jun 4–15 US Particle Accelerator School (USPAS), Boulder, Colorado (uspas@fnal.gov; <http://fnalpubs.fnal.gov/uspas>)
- Jun 18–22 2001 Particle Accelerator Conference (PAC 2001), Chicago, Illinois (Catherine Eyberger, Conference Coordinator, Argonne National Laboratory, Bldg. 401, 9700 S. Cass Avenue, Argonne, IL 60439 or pac2001@aps.anl.gov; <http://pac2001.aps.anl.gov/>)
- Jun 30–Jul 21 APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass, Colorado (Cynthia M. Sazama, MS 122, Fermilab, Box 500, Batavia, IL 60510-0500 or sazama@fnal.gov)
- Jul 8–Aug 5 Aspen Summer Workshop on Electroweak Symmetry Breaking and TeV Scale Physics After LEP, Aspen, Colorado (bagger@jhu.edu; <http://andy.bu.edu/aspen/aspen.html#workshops>)
- Jul 23–28 20th International Symposium on Lepton and Photon Interactions at High Energies (Lepton Photon 01), Rome, Italy (lp01@Inf.infn.it; <http://www.lp01.infn.it/>)
- Aug 13–24 29th SLAC Summer Institute on Particle Physics: Exploring Electroweak Symmetry Breaking (SSI 2001), Menlo Park, California (ssi@slac.stanford.edu; <http://www-project.slac.stanford.edu/ssi/2001/>)
- Aug 26–Sep 8 European School of High-Energy Physics, Beatenberg, Switzerland (Claire Earnshaw, School of Physics, CERN/DSU, 1211 Geneva 23, Switzerland (Claire.Earnshaw@cern.ch; <http://www.cern.ch/PhysicSchool/>)