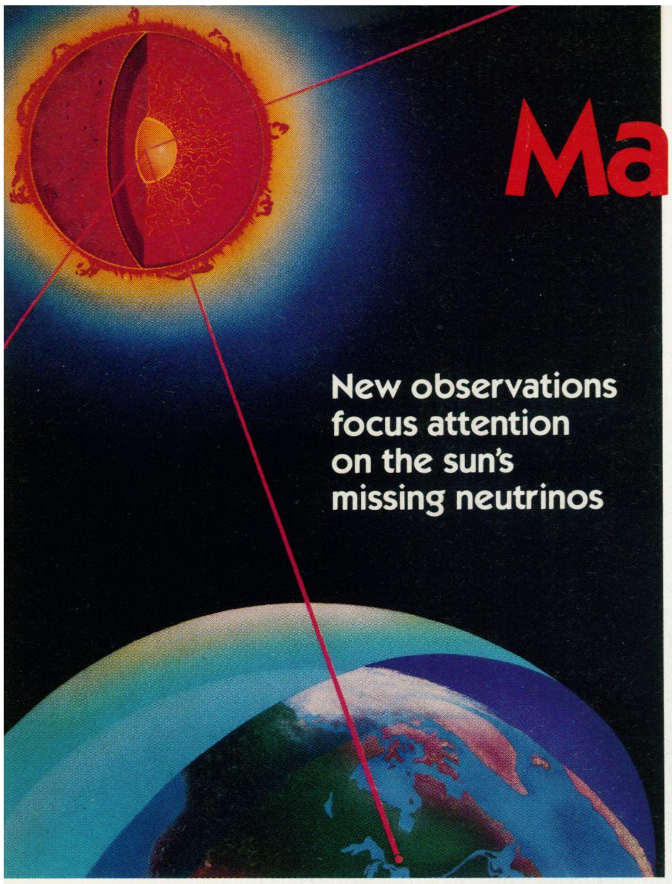
Making Sunshine

By IVARS PETERSON

New observations focus attention on the sun's missing neutrinos



Above: Thermonuclear fusion at the sun's core generates neutrinos, which rain down on the Earth's surface.

What makes the sun shine?

According to the standard solar model, the nuclear engine at the sun's center pumps out a tremendous amount of energy. In this high-temperature, high-pressure environment, protons (the nuclei of hydrogen atoms) fuse to create deuterons (proton-neutron pairs), which then combine with protons or other deuterons to produce heavier atomic nuclei, and so on. Each step in this chain of nuclear fusion reactions releases energy.

But something may be fundamentally wrong with this picture. Theoretical calculations, based on the types of nuclear reactions expected at the sun's core, indicate the sun should emit about 2 percent of its energy in the form of neutrinos—elusive particles that interact only feebly with matter. Yet the number of solar neutrinos actually detected at Earth's surface appears significantly smaller than theory predicts.

The case of the missing solar neutrinos ranks as arguably the most puzzling problem in astrophysics. Is there a basic flaw in the theory of how stars generate energy? Or do neutrinos behave in peculiar ways not yet understood? Solar-neutrino experiments now in progress and others soon to start will probably settle these questions in the next few years.

"The whole subject is coming together experimentally and theoretically," says John N. Bahcall of the Institute for Advanced Study in Princeton, N.J. "We're clearly at a time of very rapid change."

For nearly two decades, starting in 1968, the only indication of something mysterious going on came from a single neutrino detector — a huge tank of dry-cleaning fluid (perchloroethylene) installed nearly a mile underground in the Homestake gold mine near Lead, S.D. Every two months, Raymond Davis Jr. of the University of Pennsylvania in Philadelphia and his team go down the mine to extract a sample of the fluid. They analyze the material, looking for signs of the telltale reaction between a neutrino and a chlorine-37 nucleus that produces radioactive argon-37 and an electron. The number of neutrinos detected in this long-running experiment is consistently only a quarter to a third of the number expected.

In 1986, Japan's Kamiokande II neutrino detector, which uses ordinary water, began functioning. This year, members of the Kamiokande collaboration reported a neutrino flow for 1987 and half of 1988 amounting to only half that expected theoretically. The new data, published in the July 3 PHYSICAL REVIEW LETTERS, represent the first experimental confirmation that there really is an unexplained solar-neutrino deficit.

Although the Kamiokande measurements have a large uncertainty and cover only a few years, they overlap 450 days of the chlorine detector data. "We have for the first time two different detectors operating, and they give consistent results," says Lincoln Wolfenstein of Carnegie Mellon University in Pittsburgh. "That's very reassuring."

Moreover, because the Kamiokande detector, unlike the chlorine experiment, provides information about the direction in which neutrinos travel, it furnishes clear-cut evidence that the observed neutrinos actually come from the sun. Those observations offer the first experimental confirmation that the sun's energy does originate in nuclear reactions.

One of the more intriguing aspects of the solar-neutrino problem is the possibility that the neutrino flow from the sun varies from time to time. Data from the chlorine detector suggest that the number of neutrinos increases when the solar sunspot cycle is at a minimum.

"We had high results 11 years ago, and we had high results from the end of 1986 until the beginning of 1988," Davis says. Now, with the solar cycle at its peak, the number of neutrinos detected should fall off, he says. But because researchers need nearly a year to analyze a sample, it's too early to see if the trend holds up.

Bahcall, for one, finds Davis' data statistically unconvincing. "I have bet a bottle of the best French wine that the correlation is not physical, that it's a fluke," Bahcall says. The standard model of the sun's inner workings, to which Bahcall has made a considerable contribution, provides no plausible mechanism by which such variations could occur.

Even more controversial is the hint of a correlation between neutrinos and solar flares — gigantic outpourings of matter and energy from the solar surface. Large solar flares occur most often near the beginning and end of a solar cycle's peak period.

Davis detected a neutrino increase in 1972 that happened to coincide with one of the largest solar flares detected in the last few decades. The present solar cycle has featured several large flares, and Davis will look for any changes in the neutrino signal associated with those outbursts. Searches for a correlation between large solar flares and neutrino events observed at Kamiokande so far show no hint of a link.

Scientists have proposed a variety of solutions for the mystery of the missing neutrinos. Wolfenstein and Eugene W. Beier of the University of Pennsylvania, writing in the July PHYSICS TODAY, put the proposals into two broad categories: those that blame the sun and those that blame the neutrino.

Solar scientists use what they call the standard solar model to account for the sun's behavior and to calculate the expected neutrino flux. In the latest version of the model, Bahcall and Roger K. Ulrich of the University of California, Los Angeles, start with the assumption that the primordial sun was spherical and had an even distribution of chemical elements.

They deduce the abundance of heavy elements from recent observations of the solar surface, but allow the ratio of hydrogen to helium to vary. Trying various initial conditions, they calculate how their model sun evolves.

New knowledge leads to refinements of the model. "The solar model has been changed every year or two for the last 25 years that I've been working on it," Bahcall says. "But the changes have not been large."

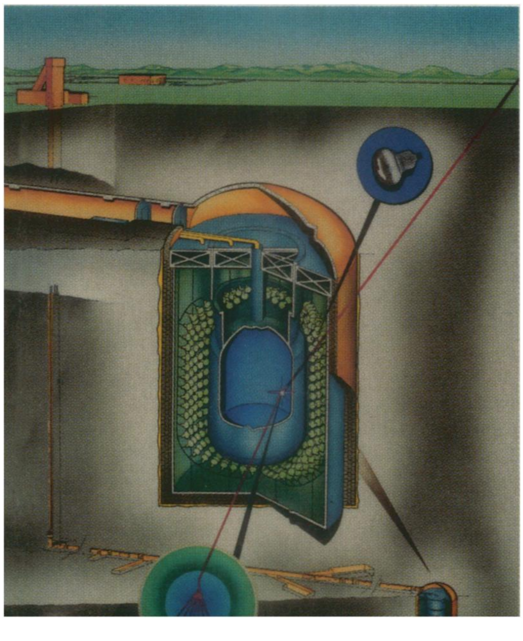
To account for the observed solar-neutrino deficit, theorists have proposed a number of "nonstandard" solar models. For example, the sun may have a different composition, internal temperature or pattern of convection currents than assumed in the standard model. Any of these factors could reduce the expected neutrino flux.

Indeed, both the Kamiokande and chlorine detectors are sensitive only to a small portion of the neutrinos produced by the sun. They pick up mainly the high-energy neutrinos resulting from the nuclear reaction producing boron-8. The rate of that reaction happens to be particularly sensitive to the sun's temperature at its core.

Helioseismology – observations of the way the sun's surface rises and falls in a pattern of oscillations – provides one of the best checks on these nonstandard models by supplying information about the sun's internal structure, for example, how deep the sun's convective zone goes. Solar-oscillation data have already ruled out several proposed nonstandard solar models. As these data get better – particularly for conditions near the sun's core, where the greatest uncertainties lie – more nonstandard models are likely to fall.

On the other hand, the standard solar model seems to fit the oscillation data well. "Preliminary indications are that the standard solar model, to the accuracy to which we need it for predicting neutrino fluxes, has been verified as far as helioseismology can presently go," Bahcall says.

To detect neutrinos, the proposed Sudbury Neutrino Observatory will use 1,000 metric tons of heavy water stored in an acrylic vessel more than a mile underground.



Images: Chalk River Nuclear Laboratories/Atomic Energy of Canada Ltd.

One initially promising idea that no longer looks so attractive is the possibility of the existence of previously undetected particles known as weakly interacting massive particles, or WIMPs. Particles in this class would presumably accumulate at the sun's center, slowing the nuclear reactions and lowering the sun's central temperature. But solar-oscillation data don't support the idea that the solar interior is cooler than postulated in the standard solar model.

"The idea of weakly interacting particles in the more general context of [the invisible] dark matter in the universe is still a very exciting possibility," Wolfenstein says, "but the particular application to the sun seems very artificial." However, he cautions, "our job is to find out what the world is like, not what we want it to be like."

Alternatively, it's possible the standard solar model is fine and that neutrinos instead change their identity in some fashion on their way to Earth. The lack of theoretical and experimental certainty concerning even such fundamental neutrino properties as mass and magnetic moment leaves lots of room for speculation.

Neutrinos come in three varieties, or "flavors": one type associated with electrons, another with muons and a third with tau particles. Each neutrino type interacts with matter somewhat differently. In one proposal, a neutrino can undergo a quantum-mechanical process that changes its flavor or causes it to oscillate back and forth between two flavors. Thus, if some of the neutrinos heading toward Earth were to change their flavor along the way, instruments designed for detecting only certain types of neutrinos would miss much of the signal.

No one has yet found evidence for such flavor transformations or oscillations. The question of whether such a transformation could occur is also tied up with the unanswered question of neutrino mass. Although many scientists assume the neutrino mass is zero, there's no compelling theoretical reason why it should be and no experimental evidence directly supporting this notion.

"We don't know of any profound reason why the neutrino mass should be zero," Beier says. "In fact, extensions of the standard solar model even allow for non-zero neutrino mass."

The neutrino may also have a spin and a small magnetic moment, which means the neutrino may behave like a tiny compass needle. One possible explanation for the apparent correlation of the neutrino signal with the sunspot cycle is that enhanced magnetic activity during peak periods may influence neutrino spins. Earth-based detectors tuned to one neutrino spin orientation would not pick up neutrinos with flipped spins. But such an effect would mean the neutrino has a relatively large magnetic moment.

"A neutrino magnetic moment can't be ruled out on the basis of any experiment," Wolfenstein says. "But there's no reasonable theory that gives such a large magnetic moment for the neutrino."

Scientists will need more observations of a greater variety of neutrinos to help settle the solar-neutrino question. "We still, in fact, have very little information," Wolfenstein says. "We're really just now beginning to attack the problem by doing different experiments."

One crucial experiment has just started in the Baksan underground laboratory in the Soviet Union's North Caucus region. There, researchers search for neutrinos by observing their interactions with 60 tons of metallic gallium, which is sensitive to a broader range of neutrinos than either the chlorine or Kamiokande detectors.

"The Russians have done a number of experiments, and they expect to get a result by the end of this year," Bahcall says. "And that will be decisive [in establishing whether the solar model is correct], but we have a few more months to wait."

A second gallium experiment, known as Gallex, is under construction in Italy at the Gran Sasso underground laboratory in the Appenines east of Rome. This experiment uses 30 tons of gallium in an aqueous gallium chloride solution and should be in operation next year.

The proposed Sudbury Neutrino Observatory would sit 6,800 feet underground in a nickel mine near Sudbury, Ontario, using a heavy water (deuterium oxide) detector to measure the same kind of neutrinos observed at the Kamiokande detector. Its design allows for the detection of certain transformations from one variety of neutrino to another – if they occur.

"These experiments are going to give us a lot of very important new information," Beier says. "In my view, it's a no-lose game. We're going to learn something – whether it's solar physics or particle physics."

"This is clearly going to be a revolutionary time," says Bahcall, whose book on neutrino astrophysics has just been published. "When the gallium results are known, the most appropriate thing will be to tear out at least one chapter of the book, because it will mean that one of the major ideas is wrong. But we don't know which chapter yet." ☐