

SOLAR NEUTRINO UPDATE: THREE DETECTORS TELL THREE STORIES

For 17 years, a 600-ton vat of cleaning fluid in the bowels of a South Dakota gold mine was the only detector on Earth looking at neutrinos from the Sun. And what Raymond Davis and his colleagues at the Homestake gold mine reported year after year was very puzzling: Their long-term average capture rate from 1970 through 1985 was 0.472 ± 0.037 solar neutrinos captured per day. But the "standard solar model" predicted, with considerable confidence, that the Homestake detector ought to be seeing about 1.8 neutrinos from the Sun per day. Allowing for the uncertainties of the standard solar model, 1.2 captures per day was the very least

the theorists would find comprehensible in the light of what they thought they knew about how the Sun works.

When Lincoln Wolfenstein (Carnegie-Mellon University) and Eugene Beier (University of Pennsylvania) summarized the situation for our readers last year (PHYSICS TODAY, July 1989, page 28), the Homestake detector's long-term average was still far below what the standard solar model could explain, even though the group had averaged about 0.9 solar neutrino captures per day in its most recent year-and-a-half of running. Over the years since 1970, the Homestake capture rate has, in fact, exhibited several wide swings. (See the figure on

page 19.)

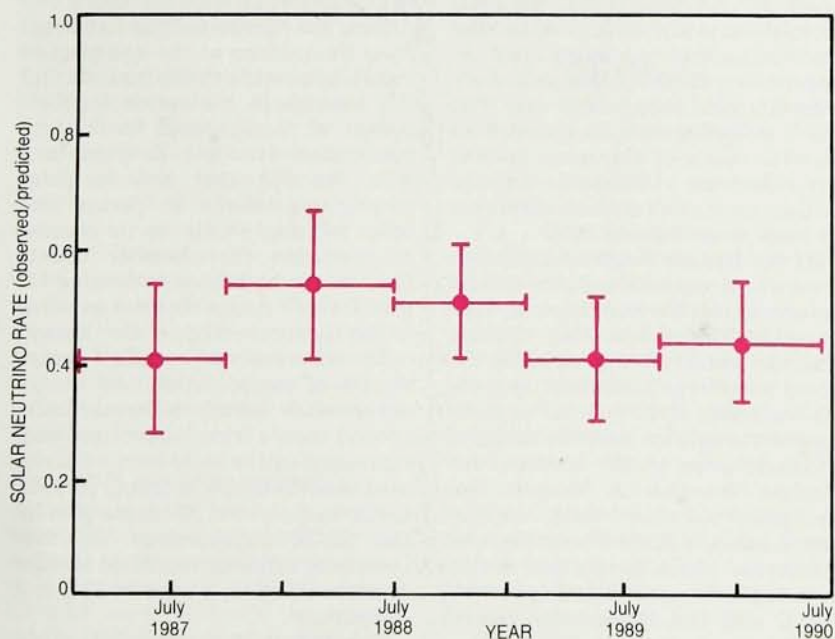
Looking at this time-varying flux plotted together with the well-known 11-year cycle of sunspot activity, one might make a statistical case for an *anticorrelation* between the abundances of sunspots and solar neutrinos. Such a bizarre connection would be even more difficult to understand than the overall shortage of solar neutrinos, unless one imagines, as some theorists have, that the neutrino has a nonzero magnetic dipole moment much larger than well-established particle theory can comfortably accommodate.

More detectors

Now there are three solar neutrino detectors in action, and a fourth is about to start. Each of the three operating detectors appears, at first glance, to be telling a different story. But, like the pieces of a good murder mystery, these disparate clues may all be pointing to a tidy solution of the 20-year-old "solar neutrino problem."

At the beginning of 1987, the Kamiokande zinc-mine detector in Japan, which had started its life looking for proton decay, began to serve as a solar neutrino detector. At the time of last year's article by Wolfenstein and Beier, the "Kamiokande II" collaboration had just reported its first results. (Beier is a member of the University of Pennsylvania's contingent at Kamiokande.) In the first 450 days of running, the group saw just under half the neutrino flux expected from the standard solar model. This was in good agreement with the Homestake data for the same period, but it was roughly twice the long-term Homestake average. Perhaps, some people said, the solar neutrino problem was only half as bad as it had seemed in earlier years.

Last month the Kamiokande group reported on an additional 590 days of running.¹ The new results look very much like the old. (See the figure on this page). Having now monitored solar neutrinos continuously for $3\frac{1}{2}$



Kamiokande II solar neutrino detector in a Japanese lead mine had been monitoring solar neutrinos since the beginning of 1987. The rate of observation of neutrinos from the direction of the Sun (with isotropic background subtracted) is shown here normalized to the prediction of the "standard solar model." One sees only about half as many solar neutrinos as the model predicts. These results show no evidence of the kind of time dependence suggested by the twenty years of solar neutrino data accumulated by the chlorine detector in the Homestake, South Dakota gold mine.

years, the group finds no evidence for the kind of temporal variation recorded by the Homestake detector. The Kamiokande flux holds fairly steady at about half the rate predicted by the standard solar model.

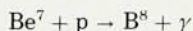
Different thresholds

Direct comparison between the solar-neutrino fluxes recorded by various detectors is problematical, because different detectors have different neutrino-energy thresholds. They are sensitive to different parts of the solar neutrino spectrum. Kamiokande II is a 3-kiloton water Čerenkov detector. Its array of photomultiplier tubes looks for Čerenkov light from electrons elastically scattered by incident neutrinos. Compared to the Homestake detector, which accumulates argon-37 atoms produced by the reaction



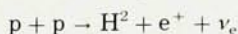
the water Čerenkov detector has the great advantage of recording the direction and energy (and even the time) of the recoil electron. But it pays the price of having a much higher energy threshold. An incident neutrino must have an energy of 7.3 MeV, at the very least, to produce a detectable recoil electron in Kamiokande II.

The energy threshold of the Homestake detector is an order of magnitude lower: 0.814 MeV, the minimum neutrino energy required for the chlorine-argon transmutation. (The detector liquid is C_2Cl_4 , the cleaning fluid perchloroethylene.) But even 0.814 MeV is a very high energy relative to the bulk of the neutrinos the standard model tells us the Sun is spewing out. Both of these detectors are sensitive primarily to the relatively few high-energy neutrinos emitted in the beta decay of boron-8 nuclei produced in the solar core by the infrequent reaction



The rate of B^8 production in the Sun is one of the less robust predictions of the standard solar model. It depends sensitively on the temperature of the solar core and other parameters that are not known with great confidence. One could therefore argue that the apparent shortage of B^8 neutrinos might be due to relatively small errors in the parameters of the standard solar model.

The most abundant source of neutrinos in the Sun is presumed to be



The spectrum of the "pp neutrinos" produced by this deuteron-formation

reaction is a firm, inescapable prediction of the standard solar model. It cannot be altered significantly by fiddling with parameters within the constraints imposed by the observable properties of the Sun. If we see too few pp neutrinos, the theorists either have to admit that everything they thought they knew about main-sequence stars like the Sun is wrong, or else they have to conclude that neutrinos do some sort of exotic vanishing act in transit, *after* they have been produced by conventional astrophysical mechanisms.

The first gallium detector

Thus the search for pp neutrinos from the Sun is very important, for both astrophysics and neutrino physics. The problem is that these neutrinos all have energies less than 0.42 MeV, well below the thresholds of chlorine or water Čerenkov detectors.

That's what makes the new gallium detectors so attractive. A neutrino traversing a tank of liquid gallium has a minuscule chance of transmuting a gallium-71 nucleus to germanium-71 by the reaction



The handful of germanium atoms thus engendered during a period of exposure to solar neutrinos can be extracted and counted with the same astonishing precision that makes the Homestake chlorine experiment so impressive. Happily, the gallium-71 transmutation threshold is only 0.23 MeV, allowing such a detector to monitor much of the solar pp-neutrino spectrum. Unhappily, a ton of gallium costs a half-million dollars—a lot more than cleaning fluid.

At the Baksan Neutrino Laboratory under a mountain in the Soviet Caucasus, the Soviet-American Gallium Experiment has been running with the initial 30 tons of its 60-ton liquid metallic gallium detector since the beginning of the year. (The melting point of gallium is 30 °C.) SAGE is a collaboration of the Institute for Nuclear Research in Moscow, the University of Pennsylvania, Los Alamos, Louisiana State University and Princeton. Davis, the pioneer of this business, is now participating in both SAGE and the Homestake experiment.

In August, at the XXVth International Conference on High Energy Physics in Singapore, V. N. Gavrin (INR, Moscow), leader of the SAGE experiment, added yet another chapter to the mystery of the missing solar neutrinos. In its first five months of exposure, Gavrin reported, the 30 tons of gallium had harvested

essentially no solar neutrino signal at all!

Of course at this early stage one is confronting the statistics of small numbers. The standard solar model predicts that the capture rate in a gallium detector should be 132 ± 19 solar neutrino units. (One SNU is defined as one capture per second per 10^{36} target atoms.) In the present configuration of the SAGE system, 132 SNU translates into a prediction of 20 germanium-71 decays counted in five months of exposure.

No pp neutrinos found

The SAGE group's proportional counter did indeed record precisely 20 counts in the analysis of the five-month exposure. But they attribute all these counts to background sources, leaving no clear sign of solar neutrinos thus far. Germanium-71 has a half-life of 11 days. Because they are looking for a handful of atoms in tons of liquid, the experimenters add a few micrograms of stable germanium to serve as a carrier and monitor of the chemical extraction. Once a month the vats of liquid gallium are chemically treated to collect all the germanium, which is then hydrogenated to form GeH_4 , a gas (very much like methane) well suited to serve as the ionizing medium in a proportional wire chamber.

Thus the "germane" gas extracted from the gallium at the end of each month becomes both the medium and the message in the search for Ge^{71} decays. It is monitored for 60 days (more than five Ge^{71} lifetimes) in a wire chamber that records pulse heights engendered by decays and other ionizing events. In its present configuration the chamber counts Ge^{71} decay candidates by looking for the 10.4-keV Auger electron expelled in the K-capture mode of Ge^{71} decay.

The occurrence of true Ge^{71} decays should, of course, exhibit an 11-day exponential falloff, whereas background counts from longer-lived contaminants will be more evenly distributed over the 60-day counting periods. Unfortunately, the 20 counts seen by the SAGE collaboration for five-months of exposure exhibited no sign whatsoever of an 11-day radioactive component.

The fact that the number of observed counts equals the solar-model prediction, though it made for some confusion at Singapore, is purely coincidental. Had one chosen to monitor each month's germanium extraction for 120 days instead of 60, there would have been twice as many background counts. The background rate seen at Baksan is, in fact, just about what was

expected from contaminants such as radon and longer-lived germanium isotopes. If the solar-model prediction had proven true, the experiment's signal-to-noise ratio would have been about 5:1 in the first two weeks of each counting period.

Upper limits

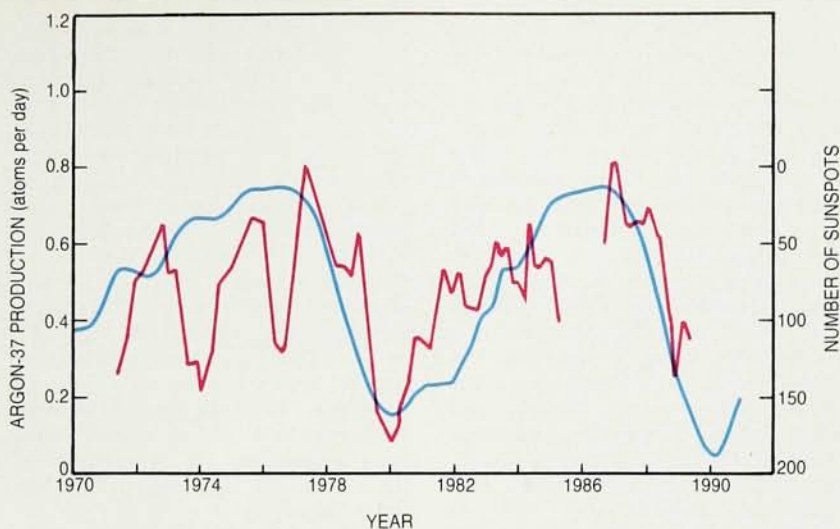
What is one to make of all this? The SAGE collaboration translates its early results into upper limits on the solar neutrino flux accessible to gallium detectors: The ^{132}SNU prediction for neutrinos from all accessible reactions and decays in the Sun is just about the 2-standard-deviation upper limit derived from the absence of a signal in the SAGE data. About half of this total prediction—70.8 SNU—is the ironclad prediction for the capture of pp neutrinos. It turns out that 70 SNU is the 1-standard-deviation upper limit of the solar neutrino capture rate derived from the SAGE data.

This disturbingly negative preliminary result cries out for more data. The SAGE group is about to add 30 more tons of gallium to the detector, and the counting system is being upgraded to recognize the lower-energy Auger electrons from the L-capture mode of Ge^{71} decay. These two improvements together should provide a fourfold increase in the SAGE experiment's data rate by the end of the year.

That's just about when Gallex plans to begin taking data. Gallex is a 30-ton gallium detector built by a predominantly European collaboration under the Gran Sasso d'Italia in the Abruzzi Apennines, the mountain on whose summit the Germans snatched Mussolini from captivity in 1943. Gallex's 30 tons of gallium will be in the form of GaCl_3 in hydrochloric acid solution. Germanium nuclei formed by solar neutrinos will escape the solution as GeCl_4 gas, which is collected and converted to GeH_4 for counting.

Resonant neutrino oscillation

If Gallex and the further accumulation of SAGE statistics confirm what appears to be a significant suppression of pp neutrinos, one will be forced to take very seriously the mechanisms that have been proposed for rendering electron neutrinos invisible as they make their way out of the Sun. Well-established particle theory tells us that neutrinos come in three "flavors"—associated respectively with the electron, the muon and the much heavier tau lepton. The chlorine and gallium detectors can see only left-handed *electron* neutrinos; hence the



Possible anticorrelation between the abundance of sunspots and the capture of solar neutrinos is suggested by two decades of data from the Homestake solar neutrino detector in a South Dakota gold mine. The red curve shows the *per diem* rate at which argon-37 atoms are produced in the detector's 600 tons of perchloroethylene by the collision of incident neutrinos with chlorine nuclei. The blue curve (note the inverted scale at right) plots the sunspot population. The well-known 11-year cycle of solar activity is evident. If this curious correlation is real, it might be due to the flipping of neutrino spins in the Sun's magnetic field. That would require the neutrino to have a surprisingly large magnetic dipole moment.

subscript "e." ("Left-handed" means that spin and momentum are antiparallel. Antineutrinos are right-handed. Right-handed neutrinos, as distinguished from antineutrinos, would have no interactions with matter.) Neutrinos of other flavors can scatter elastically in detectors like Kamiokande II, but with a much smaller cross section.

The Mikheyev-Smirnov-Wolfenstein theory (described in Beier and Wolfenstein's article) points out that electron neutrinos can be efficiently converted into muon neutrinos by resonant interaction with electrons in the Sun *if* there is sufficient mass difference and mixing between the flavor eigenstates. The nonzero neutrino masses required for the MSW resonant mechanism are much smaller than the 9-eV upper limit on the electron neutrino recently determined from the tritium beta-decay spectrum by Hamish Robertson and his colleagues at Los Alamos.²

The MSW mechanism is widely regarded by particle theorists as a modest and natural extension of the "standard model" of the elementary particles. The standard particle model assumes for simplicity that all neutrinos are massless and that their flavor eigenstates do not mix. But quarks are known to exhibit just this kind of mixing, and there is no strong

reason to believe that neutrinos have absolutely no mass. Experimenters have long been looking for the oscillations between neutrino flavors that could occur, even in a vacuum environment, if there is mixing between neutrinos of different mass. But not until the 1985 paper by S. P. Mikheyev and A. Yu. Smirnov (both at INR) did people realize that resonant interaction with electrons in the solar plasma might well produce enough flavor conversion to solve the solar neutrino problem.

A solution?

A recent paper by John Bahcall (Institute for Advanced Study, Princeton) and Hans Bethe (Cornell) invokes the evidence that solar neutrino suppression appears to be least severe at Kamiokande, the detector with the highest energy threshold.³ This observation, they argue, favors the "nonadiabatic solution" of the MSW theory over its adiabatic alternative, because the latter would act most severely on the most energetic neutrinos. The Kamiokande group has come to much the same conclusion from a detailed examination of the recoil-electron spectrum they see.⁴ "Adiabatic," in this context, means that the neutrino's passage through the resonant region of solar electron density is gradual enough to keep the

neutrino always in its smoothly varying mass eigenstate as it undergoes its metamorphosis from ν_e to ν_μ .

Bahcall has played the leading role over the years in calculating the standard-solar-model predictions for various detectors. "I've written more than a hundred papers, and a book, on solar neutrinos," he told us. "But this is the first one I've called 'A Solution of the Solar Neutrino Problem.'" Neutrino oscillation between ν_e and ν_μ , in the Sun or in vacuum, is determined by two parameters: the mass difference and the mixing angle between the states. Bahcall and Bethe find a region of this parameter space that explains both the Kamio-kande data and the long-term average of the Homestake data.

Even better, Bahcall told us, the parameters thus constrained predict the severest MSW suppression for the gallium detectors: They should see an order of magnitude less flux than the standard solar model predicts. With a plausible choice of small mixing angle, the Bahcall-Bethe MSW solution yields a mass difference on the order of 0.001 eV between the two neutrino flavors.

Sunspots

The MSW theory does not, however, address the question of how the solar neutrino flux might be correlated to the 11-year cycle of sunspot activity. In any case, doesn't the constancy of the Kamiokande data contradict the Homestake observation of considerable variation from year to year? "Not necessarily," says Kenneth Lande (University of Pennsylvania), who works on both the Homestake experiment and SAGE. He invites us to suppose, for the sake of argument, that the mechanism which correlates solar neutrino suppression with sunspots works only on low-energy neutrinos, leaving the B^8 neutrinos unaffected. The standard solar model tells us that the Homestake detector should see about 6 SNU of B^8 neutrinos and 1.8 SNU from lower-energy sources. But the Kamiokande data cut this B^8 prediction roughly in half. If we now say that the low-energy neutrinos are untrammelled in years of quiet Sun and almost completely suppressed when sunspot activity is high, Lande points out, we are left with something like the factor-of-two swings seen in the Homestake data.

Solar astrophysicists conjecture that the cyclic character of sunspot activity reflects a regular variation of the magnetic field intensity in the Sun's convective zone. If the neutrino had a sufficiently large magnetic dipole moment, its spin could flip as it

traversed the solar magnetic field, making a left-handed neutrino right-handed and thus invisible. The deficit of solar neutrinos would be worst just when the abundance of sunspots tells us the solar magnetic field is at a maximum.

Such a scheme has in recent years been elaborated at the Institute for Theoretical Physics in Moscow by Mikhael Voloshin (now also at the University of Minnesota's Theoretical Physics Institute), Mikhael Vysotsky and Lev Okun as a possible explanation for the variability of the Homestake data. To flip its spin in the solar magnetic field, the neutrino would need a magnetic dipole moment on the order of $10^{-11} \mu_B$, where μ_B is the Bohr magneton.

Ordinarily we think of the neutrino as having no electromagnetic interactions whatsoever. One can, however, calculate neutrino magnetic moments on the order of $10^{-19} \mu_B$ with modest extensions of conventional theory. The additional eight orders of magnitude required by the conjecture of Voloshin, Vysotsky and Okun "would not be a fair estimate of its implausibility," Bahcall argues, "but it is some indication of [the theory's] lack of inevitability."⁵ In any case, Okun admits, the observational evidence for cyclic variation of the solar neutrino flux is not yet compelling.

Prospects

All four solar neutrino detectors of the present generation suffer from painfully slow rates of data acquisition. Meager statistics cloud all the conclusions thus far. By mid-decade, however, things should be a lot better. The most massive and ambitious detector now under construction is the Sudbury Neutrino Observatory, in a very deep mine shaft 200 miles north of Toronto. The SNO detector will have 1000 tons (several hundred million dollars' worth) of very pure heavy water in a transparent vessel surrounded by 5000 tons of light water and an array of photon detectors. Canada's surplus of heavy water in a depressed world market for its Candu heavy-water nuclear power reactors has made the project financially feasible.

When it begins operation in 1995, SNO should see many thousands of events per year. The deuterium target nuclei will be particularly useful for distinguishing between charged-current interactions, which require electron neutrinos, and neutral-current scattering, which is "flavor blind."

Various mineral deposits in the Earth can be thought of as solar

neutrino detectors that have been running unattended for millions of years, just waiting for the geochemists to analyse the results. The first of these geochemical experiments, originally suggested by George Cowan (Los Alamos) and Wick Haxton (University of Washington), is just getting under way at Los Alamos. The scheme is to process thousands of tons of molybdenite ore from a very deep deposit in Colorado with the goal of harvesting a few million atoms of technetium-98. Tc^{99} is a spontaneous fission product of uranium, but Tc^{98} , which has a half-life of 4 million years, is presumed to come only from the interaction of a molybdenum-98 nucleus with a neutrino. An ultrasensitive mass spectrometer will cull the Tc^{98} atoms from the background of other technetium isotopes.

Counting the Tc^{98} atoms extracted from the molybdenite ore will provide a measure of the flux of B^8 solar neutrinos averaged over the last several million years. One would like to look still further back, because the standard solar model implies that the B^8 neutrino flux has been growing exponentially for the last 5 billion years, with a doubling time of 850 million years.

Paleoclimatologists are skeptical, because this scenario also requires the Sun's luminosity to have increased by 40% over the last 5 billion years. Haxton has recently suggested another geochemical experiment that might tell us about the B^8 neutrino flux variation on these very long time scales.⁶ He suggests that one look for small amounts of the (stable) isotope xenon-126 in deep telluride ores. It could only have gotten there, he argues, by neutrino interaction with tellurium-126. And because the xenon isotope is stable, the record should be essentially permanent.

"This proposal is a challenge to the geochemists," Haxton told us. "It's an exceedingly difficult measurement."

—BERTRAM SCHWARZSCHILD

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