Mercury, pp. 53–63, Vol. XIX, Number 2, March/April 1990

Neutrinos from the Sun: An Astronomical Puzzle

John N. Bahcall *Institute for Advanced Study*

Introduction

Astronomers and physicists who study the processes that generate energy in the Sun and the stars are certain that some of the nuclear reactions powering our Sun produce—among other products—significant numbers of the elusive subatomic particle called the neutrino. The study of neutrinos from the Sun has led to one of the most challenging puzzles in twentieth century astronomy, whose solution may give us new insights into the ways the stars produce energy and evolve, and into the nature of the neutrino itself.

A neutrino is a weakly interacting particle that travels at essentially the speed of light. Neutrinos are so elusive that a typical low-energy solar neutrino can travel through a thousand light years of lead before it is stopped or loses much of its energy. Neutrinos are produced on Earth by natural radioactivity, by nuclear reactors, and by high-energy accelerators. In the Sun, neutrinos are produced by the so-called *weak interactions* that occur during nuclear fusion, the process of building up heavier elements from lighter ones.[1]

Neutrino astronomy is interesting for the same reason it is difficult. Because neutrinos only interact weakly with matter, they can reach us from otherwise inaccessible regions where photons, the traditional messengers of astronomy, are trapped. Hence, with neutrinos we can look inside stars and examine directly the energetic physical processes that occur only in stellar interiors. Indeed. this is the only direct way we can study the interior of the Sun or the core of a collapsing star as it produces a supernova.

Large detectors, typically hundreds or thousands of tons of material, are required to observe astronomical neutrinos. These detectors must be placed deep underground to avoid confusing the rare astronomical neutrino events with the background interactions caused by cosmic rays and their secondary particles,[2] which are relatively common near the surface of the Earth.

[1] To be technically precise, we should note that there are three types of neutrinos known, each associated with a different particle from a class physicists call leptons, electrons, muons, and taus. (Leptons are a family of particles that are affected by gravitational, electromagnetic, and weak nuclear forces, but not by the strong nuclear force, which, for example, holds protons and neutrons together in the nucleus of an atom.)

[2] Cosmic rays are high-speed particles (such as protons, electrons, etc.) that hit the Earth from space. Frequently, the collision of such a particle with a molecule of air in the Earth's atmosphere produces a new particle or particles, which are then called *secondaries.*—Ed.

For two decades, the only operating solar neutrino experiment (in a gold-mine shaft near Lead, South Dakota) yielded results in conflict with the most accurate theoretical calculations. That is, the experiment detected significantly fewer neutrinos from the Sun than we expected, based on our understanding of nuclear reactions inside the Sun. This conflict between theory and observation, which has recently been confirmed by a new experiment, is known as the *solar neutrino problem.*

More is known about the Sun than about any other star and the calculations of neutrino emission from the solar interior can be done with relatively high precision. Hence, the solar neutrino discrepancy has puzzled (and worried) astronomers who want to use neutrino observations to try to understand better how the Sun and other stars shine. The solar neutrino problem could literally be a clue to something new under the Sun!

In addition to neutrinos from the Sun, astronomers have long predicted that there should be an enormous outpouring of neutrinos from the explosions of massive stars called supernovae. The observations of neutrinos from Supernova 1987A, the first supernova visible to the naked eye in almost 400 years, have given scientists their first taste of extra-galactic neutrinos. While that story is outside our present scope, it does reinforce the importance of neutrino astronomy for a full understanding of the cosmos.

To study particles like neutrinos on Earth scientists generally rely on large particle accelerators in which energetic collisions create "beams" of the desired particles or on massive fission reactors in which energy is released by the breaking apart of heavy nuclei.

However, neutrinos from the Sun and from supernovae provide cosmic particle beams for probing the weak interactions of particles with energies and on time scales that cannot be achieved with traditional laboratory experiments. Since neutrinos from the Sun and from supernovae travel astronomical distances before they reach the Earth, experiments performed with these particle beams are sensitive to weak interaction phenomena that require long path lengths for their effects to occur. For example, if neutrinos have tiny masses, so small that they are unmeasurable in the laboratory (instead of being mass-less as we have thought them to be), the effects of this tiny mass could in principle be studied with solar neutrinos.

We shall concentrate on solar neutrinos because the Sun is the only observable steady source of neutrinos. However, the experimental techniques are the same for studying solar and supernova neutrinos and many of the theoretical considerations are similar.

Where Do We Stand?

Astronomers who study neutrinos theoretically and observationally express the measurements of neutrinos being captured by a detector in terms of the solar neutrino unit, or SNU. The SNU value tells us how many neutrinos are expected (or observed) to be captured per target atom in our detector each second. Since neutrinos are elusive, we expect any given atom to have very few interactions with neutrinos and so a SNU is defined to be a very small unit: 10^{-36} events per target atom per second.

In the pioneering neutrino detector that Ray Davis and his coworkers assembled in South Dakota, the detector consists of a swimming-pool size vat of a chlorine compound. When a neutrino interacts with a chlorine nucleus (^{37}Cl). the result is an atom of radioactive argon (^{37}Ar) whose presence can be found with instruments surrounding the chlorine vat. Our best prediction for the rate of capturing neutrinos from the Sun in the chlorine is 7.9 SNU, $\pm$ 2.6 (total theoretical error). What Ray Davis and his associates detect is 2.1 SNU $\pm$ 0.9 (3-sigma error).

The disagreement between the predicted and observed rates constitutes the solar neutrino problem. As of now, there is no generally accepted solution to this problem, although, as we shall see, a number of interesting possibilities have been proposed.

The discrepancy has recently been confirmed by a Japanese detector called Kamiokande II, which uses a different and independent technique for measuring the number of neutrinos coming from the Sun. The number of neutrinos they observe is roughly 45% ($\pm$ 15%) of what we expect.

We should note that the predictions to which we compare the observations are based on what we call the *combined standard model*, that is, the modern standard model of physics that provides a combined description of electrical and weak interaction phenomena *and* the standard model astronomers have developed for what is happening in the Sun. Could it be that one or both of these models are flawed?

Why Does Anyone Care?

The central question for solar neutrino research is easily stated. Is the solar neutrino problem caused by unknown properties of the neutrinos themselves or by a lack of understanding of the interior of the Sun? In other words, is this a case of new physics or faulty astrophysics?

Many physicists are interested in solar neutrino experiments because these observations provide a special opportunity to explore the weak interactions with a unique sensitivity. Put another way, if the neutrino should turn out to have a mass, we could detect very small neutrino masses using this technique. Experiments that use the Sun as a source of neutrinos are more sensitive than corresponding laboratory experiments because of the large distance between the source in the Sun and the target on Earth and because of the relatively low energy of solar neutrinos. In solar neutrino experiments, the weak interactions have a longer time to make their effects felt than in terrestrial experiments. The potential increase in sensitivity over feasible laboratory or atmospheric experiments is about seven orders of magnitude in neutrino masses.

From the astronomical point of view, solar neutrino experiments could test in a rigorous way the theories of how stars evolve and how nuclear energy is generated inside stars. These neutrino tests are independent of many of the uncertainties that complicate the comparison of the theory with observations of the surfaces of stars. For example, convection (the rising of hot material) and turbulence are generally believed to be important near stellar surfaces but unimportant in the solar interior. Furthermore, the effects of a star's rotation and magnetic field, which are hard to model accurately, also complicate the analysis of observations of stellar surfaces. In a sense, because neutrinos interact so weakly with ordinary matter, they allow us to "peer" deep into our Sun where the nuclear reactions are actually taking place.

Observations of solar neutrinos also constitute critical tests of the theory of stellar evolution. We know more about the Sun than about any other star. We know its mass, is luminosity, its surface chemical composition, and its age much more accurately than we can determine these crucial parameters for any other star. Moreover, the Sun is still in the simplest stage of stellar evolution: according to standard theory, it is a middle-aged main sequence star, calmly burning hydrogen without violent or rapid evolution. Thus we expect to be able to calculate what the Sun is doing more accurately than we can predict the behavior of less familiar stars that are evolving rapidly.

Modifications of the theory of stellar evolution have been proposed as possible solutions of the solar neutrino problem. None of these solutions is fully consistent with well-established physics. However, as we will see, these occasionally drastic modifications show what is at issue for astronomy. The published astronomical solutions change conventional ideas about how stars evolve, ideas that astronomers use every day in their research. In interpreting astronomical observations (made by detecting photons such as visible light), and in constructing astronomical theories, we use the theory of stellar evolution to determine the ages of stars, to interpret their compositions, to infer the evolution of galaxies, and to place limits on the chemical composition of the primordial material of the universe. Each of these basic "astronomical industries" is called into question by at least one of the proposed solutions of the solar neutrino problem.

In order that the reader may begin to form an opinion on these questions, the next three sections summarize in a qualitative way the aspects of stellar evolution theory that are necessary to predict the expected event rate in a solar neutrino experiment.

Stellar Evolution

To understand the solar neutrino problem, one needs to know the main ingredients of the theory of stellar evolution that are used in the construction of solar models.

The Sun is assumed to be spherical and to have evolved *quasistatically* (from one approximately equilibrium configuration to another approximately equilibrium configuration) for a period of about five billion years. As our star evolves. photons of radiation are lost from the surface of the star, an energy loss which in turn is balanced by energy from the fusion of protons into alpha particles (helium nuclei) in the core of the Sun. The overall reaction can be represented symbolically by the relation:

$$4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2\mathrm{e}^+ + 2\nu_\mathrm{e} + 25\ \mathrm{MeV}$$

That is, four protons are converted to an alpha particle, two positrons (anti-matter electrons), and two neutrinos, with a release of about 25 MeV (million electron volts) of energy for every four protons burned. Each conversion of four protons to an alpha particle is known as a *termination* of the chain of energy-generating reactions that accomplishes the nuclear fusion. The energy that is supplied by nuclear fusion ultimately emerges from the surface of the Sun as sunlight.

Energy is transported in the deep solar interior mainly by photons, which means that the opacity of matter to radiation is important in constructing our models. (Opacity measures the degree to which a given material is opaque to light.) Another factor to bear in mind as we examine our models is that gravity wants to pull the ball of gas which is our Sun inward; it is the thermal motion (heat) of the electrons and nuclei in the Sun that largely provides the pressure to counteract the pull of gravity.

Some of the principal approximations used in constructing standard solar models deserve special emphasis because of their fundamental roles in the calculations. In response to the neutrino crisis, each of these approximations has been investigated carefully for possible sources of departure from the standard models:

Hydrostatic equilibrium. The Sun is assumed to be in hydrostatic equilibrium, that is, the radiation and particle pressures of the model exactly balance gravity. Observationally, this is known to be an excellent approximation since a gross departure from hydrostatic equilibrium would cause the Sun to collapse (or expand) in a free-fall time of less than an hour.

Energy transport by photons or by convective motions. In the deep interior, where neutrinos are produced, energy is transported primarily by the diffusion of photons: the calculated opacity of the material at the Sun's core is a crucial ingredient in the construction of a model and has been the subject of a number of recent detailed studies. Further out, the rising of hot material must be taken into consideration.

Energy generation by nuclear reactions. The primary energy source for the radiated photons and neutrinos is nuclear fusion, although the small effects of the Sun's gravitational contraction (or expansion) are also included in our models.

Abundance changes caused solely by nuclear reactions. The Sun's interior is presumed to have been chemically homogeneous at the beginning. It follows that in regions of the model where there is no convection, changes in the local abundances of individual elements can occur only by nuclear reactions.

A *standard solar model* is the end product of a sequence of models calculated (like snapshots) over the lifetime of our Sun. The calculation of a model begins with the description of a main sequence star that has a homogeneous composition. Hydrogen burns (fuses) in the stellar core, supplying both the radiated luminosity and the thermal pressure that supports the star against the force of gravity. Successive models are calculated by allowing for composition changes caused by nuclear reactions, as well as the mild evolution of other parameters, such as the star's surface luminosity and the temperature distribution inside the star. As a result of the nuclear fusion processes at the core of the star, the models that describe later times in an evolutionary sequence have inhomogeneous compositions. In the model for the current Sun, the innermost mass fraction of hydrogen is about half the surface (initial) value because hydrogen in the center has been used up by billions of years of nuclear reactions.

A satisfactory solar model is a solution of the evolutionary equations that satisfies what astronomers call boundary conditions in both space and time. One seeks a model with a fixed mass in which after 4.6 billion years (the present age of the Sun, determined accurately from meteoritic ages) the total luminosity and the radius of the model wind up being what we observe for the Sun. The assumed initial values of such parameters as the Sun's chemical composition and the entropy (which measures the amount of disorder) are calculated again and again until an accurate description is obtained of the Sun at the present epoch. The solution of the evolution equations predicts a variety of astronomical characteristics: the initial values for the mass fractions of hydrogen, helium, and heavy elements, the present distribution of physical variables inside the Sun, the spectrum of acoustic oscillation frequencies observed on the surface of the Sun, and the neutrino fluxes.

While the physical conditions in the solar interior where the neutrinos are produced are different from the conditions of everyday life, they are not so different as to suggest that the relevant physics will contain important surprises. The central temperature is 15 million degrees Kelvin and the central density is about 150 grams per cubic centimeter.[3] As far as is known, the physics of the gaseous solar interior is relatively simple.[4]

The initial chemical composition is assumed to have been approximately the same everywhere in the Sun; the present-day surface composition is assumed to reflect the initial ratio of heavy elements to hydrogen. (The surface of the Sun is too cool for nuclear reactions to have significantly altered the composition there.) Several authors have discussed a possible solution of the solar neutrino problem in which the initial chemical composition was very nonuniform. However, no one has yet succeeded in constructing a theoretical model, consistent with all the available observations, in which the Sun's initial composition was strongly inhomogeneous.

The calculation of a standard solar model begins with an estimate of the initial fraction of the Sun's total mass that was in the form of hydrogen. (The surface measurements give only the rations relative to hydrogen of the abundances of elements heavier than helium; the abundance of helium on the solar surface cannot be measured accurately.) The model parameters are then evolved quasistatically, taking account of the composition changes and the energy released by nuclear reactions. We should note that the accuracy with which the interior calculations must be carried out is much higher than for most other applications of stellar evolution theory, because the neutrino measurements relate directly to processes occurring in the solar interior and because the calculated numbers of neutrinos are quite sensitive to the physical

[3]For comparison, the average density of the Earth is about 5.5 grams per cubic centimeter.—Ed.

[4]For readers with a technical background, we might point out that calculations of the standard model do include corrections to the equation of state that arise from electron degeneracy and plasma effects, but these corrections are small and do not significantly affect the predicted neutrino fluxes.

conditions.

The *luminosity boundary condition* states that the luminosity predicted by the model at the Sun's present age must equal the actual brightness we observe the Sun to have; this condition has a strong effect on the calculated neutrino fluxes. The reason is that both the luminosity and the neutrino fluxes are the result of nuclear reactions in the Sun's core.

Evolutionary codes (computer programs that simulate a star's evolution) have been developed by a number of different research groups in astronomy; when adjusted for differences in input parameters, the codes turn out to yield individual predictions of solar neutrino fluxes that are the same to an accuracy of about 10% or better. This means that selecting one code over another will not help us solve the neutrino problem.

It is important to realize that, both for the Sun and for other stars, the theory of stellar evolution we have developed is in satisfactory agreement with *conventional* astronomical observations. Some of the principal results from the calculations with a standard solar model that agree with observations include:

1) a model luminosity for the Sun that increases by about 40% over the five billion years our star has been shining;

2) the calculation that the abundance of helium in the Sun is 27% by mass; and

3) a complete spectrum for the p-mode (pressure) oscillations (observed in a variety of ways on the solar surface).

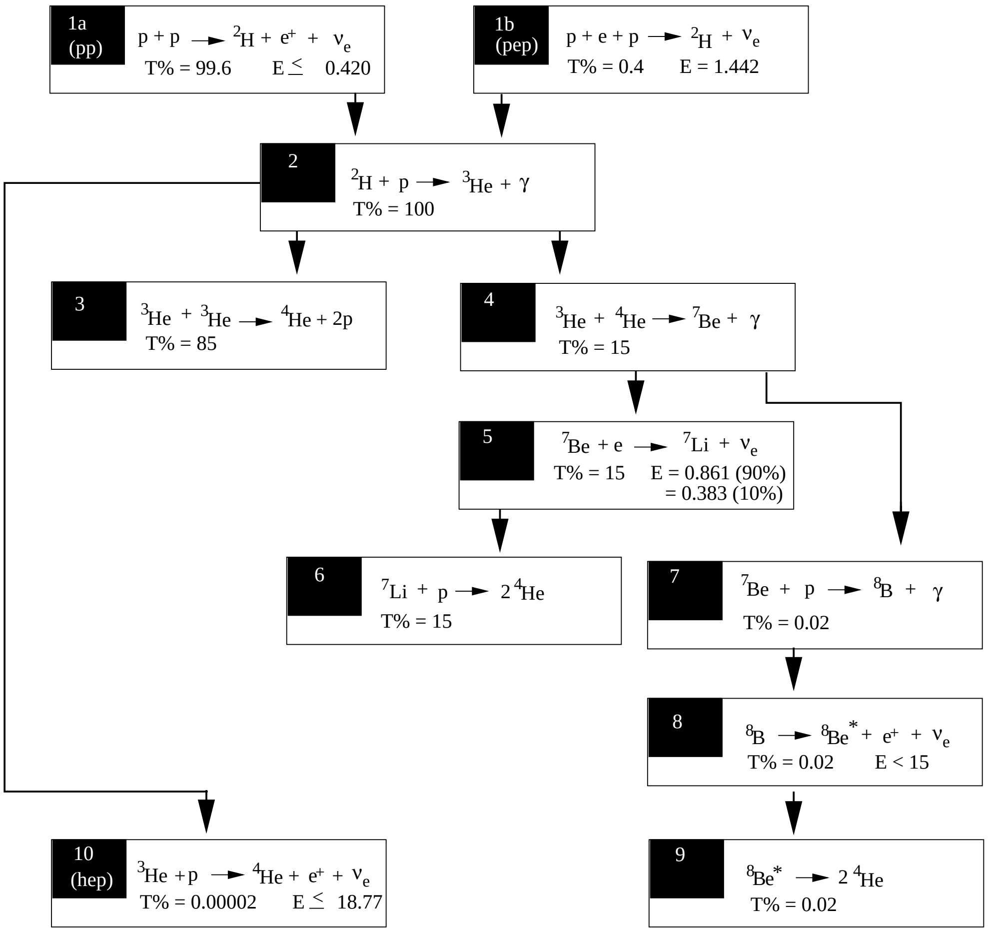
Thus the standard solar model gives a satisfactory (although necessarily incomplete) account of what is known about the Sun from photons.

Furthermore, the theory of stellar evolution has a number of successes to its credit. Its most basic achievement is a theoretical relationship between the mass and the (photon) *luminosity* of stars that is in agreement with observation over almost two orders of magnitude in mass (six orders of magnitude in luminosity). In addition, the theory successfully accounts for the distribution of known stars when they are plotted on a graph that shows their luminosity versus temperature or luminosity versus color. Since most of this plot (known technically as the *Hertzsprung-Russell diagram* or *H-R diagram*) is empty, the representation of the positions of the known stars by conventional models is a major triumph. The calculated frequencies of the surface oscillations of the Sun agree with the observed values to better than 1%, which constitutes a great success for the theory despite the fact that disagreements exist at the level of a few tenths of a percent (disagreements that might arise from processes that are unimportant for the solar neutrino problem).

The greatest achievement of the theory of stellar evolution is so overwhelming that it is usually overlooked. Astronomers use the theory routinely in interpreting astronomical observations of the physical and chemical characteristics of widely different

Table 1:

The Proton-Proton (pp) Chain in the Sun



The chart above diagrams the various steps in the nuclear reactions that convert hydrogen nuclei (protons) to helium nuclei(^{4}He) in the Sun. The process begins with either step 1a (called the **pp** reaction) or step 1b (called the **pep** reaction) and ultimately produces a helium nucleus, two positrons, two neutrinos, plus energy.
For each step, we also include **T%**, the termination percentage, which shows the relative frequency with which that reaction in the chain occurs. Thus, for example, step 3 occurs for 85% of the of the reactions that come to completion, and its alternate, step 4, occurs for 15% of the reactions that terminate.
For the steps involving the production of neutrinos, the chart also shows the energy of the neutrino released in **MeV** (millions of electron volts). The symbol γ stands for gamma rays, the form in which electromagnetic energy is produced by these reactions.

individual star types in a variety of environments, in both nearby and distant galaxies. Stellar evolution theory has been remarkably successful in providing a framework for discussing these astronomical observations without obvious inconsistencies.

The bottom line of this brief survey of the theory of stellar evolution is that only the 37Cl solar neutrino experiment, and most recently the Kamiokande II experiment, are inconsistent with the standard theory. Even this inconsistency could be just apparent. A popular scenario for explaining the solar neutrino problem (which has many variations) supposes that solar neutrinos are indeed produced in the quantity predicted by the standard solar model, but that they do not reach the Earth in the form in which they are emitted at the Sun. If something happens to the neutrinos in the solar interior or on the way to the Earth. then the standard solar model may be correct and the solar neutrino experiments could be telling us something new about neutrino propagation over large distances.

Nuclear Energy Generation and Neutrino Fluxes

As we saw, the Sun shines by converting protons into alpha particles (helium nuclei). About 600 million tons of hydrogen must be used up every second to supply the luminosity we see from the Sun. Nuclear physicists have worked for half a century to determine the details of this transformation.

The main nuclear "burning" reactions in the Sun are shown in Table I, which represents the energy-generating reactions we call the *pp chain* (since they start with two protons). This table also indicates the relative frequency with which each reaction occurs in the standard solar model. (There is another nuclear path for making helium from hydrogen called the *CNO cycle*, where the fusion of four protons to form an alpha-particle is achieved through reactions involving carbon, nitrogen, and oxygen.)

The fundamental reaction in the solar energy-generating process is the proton-proton (pp) reaction. In the pp reaction, a proton undergoes a change called a *beta-decay* in the vicinity of another proton. forming a bound system, deuterium (^{2}H)—often called heavy hydrogen, since it contains both a proton and a neutron. This reaction (number 1a in Table 1) produces the great majority of solar neutrinos; however, these pp neutrinos have energies below the detection thresholds for the ^{37}Cl and Kamiokande II experiments. New experiments, using the element gallium (^{71}Ga) as a detector, that are in progress in the Soviet Union and in Europe, are sensitive primarily to neutrinos from the pp reaction.

Most of the predicted capture rate in Ray Davis' ^{37}Cl experiment comes from the rare termination in which a beryllium nucleus (^{7}Be) captures a proton to form radioactive boron ^{8}B (reaction 7 in Table 1). The ^{8}B decays to unstable ^{8}Be [reaction 8 in Table 1], ultimately producing two alpha particles, a positron, and a neutrino. The neutrinos from ^{8}B decay have a maximum energy of roughly 15 MeV. Although the reactions involving ^{8}B occur only once in every 5000 terminations of the pp chain, the total calculated event rates for the ^{37}Cl and Kamiokande II experiments are dominated by this rare mode.

For ^{37}Cl, the ^{8}B contribution is most important because many of the neutrinos from this source are sufficiently energetic to excite a favored transition between the ground state of the nucleus ^{37}Cl and the analog excited state of ^{37}Ar (which closely resembles the ground state of ^{37}Cl). None of the more abundant neutrinos have enough energy to cause this strong analog transition. A theoretical calculation originally showed that the sensitivity for the detection of ^{8}B neutrinos is increased by about a factor of 20 by transitions to excited states. This result has been confirmed by a series of beautiful nuclear physics experiments on the four similar nuclei with atomic mass number 37.

Uncertainties in the Predictions

Is there really a solar neutrino problem or is it just a result of uncertainties in our theories? The answer is yes if the difference between the predicted and the measured capture rates of neutrinos exceeds the range of the uncertainties. The answer is no if the uncertainties exceed the discrepancy between theory and observation.

The solar neutrino fluxes calculated from the standard solar model are shown in Table 2, together with the uncertainties in those fluxes.

The flux of the basic pp neutrinos can be calculated to an estimated accuracy of 2% using the standard solar model. Thus the pp flux, the dominant flux of solar neutrinos, can be thought of as a reliable source, placed at an astronomical distance. which can be used for physical experiments on the propagation of neutrinos. It will be interesting to see what is revealed by experiments which can measure this flux.

The production rate for the rare neutrinos which we currently observe from ^{8}B beta-decay (equation 8 in Table 1) is sensitive to conditions in the solar interior. The reaction that precedes it involves a beryllium 7 nucleus merging with a proton, a process in which there is considerable electric repulsion. In fact, the particles need an energy of about 10 MeV to overcome the electric repulsion they experience, while the average thermal energy (available from the heat inside the Sun) is only about 1 keV,

Table 2:

Calculated solar neutrino fluxes.

(Numbers of neutrinos flowing through a unit area in a unit time.)

Source	**Flux** (10^{10} cm^{-2} s^{-1})
pp	$6.0(1 \pm 0.02)$
pep	$0.014(1 \pm 0.05)$
hep	8.0×10^{-7}
^{7}Be	$0.47(1 \pm 0.15)$
^{8}B	$5.8 \times 10^{-4}(1 \pm 0.37)$
^{13}N	$0.06(1 \pm 0.50)$
^{15}O	$0.05(1 \pm 0.58)$
^{17}F	$5.2 \times 10^{-4}(1 \pm 0.46)$

or 0.001 MeV. The calculated flux of ^{7}Be electron capture neutrinos is intermediate in sensitivity between the pp and the ^{8}B neutrinos. Nevertheless, the numbers in Table 2 show that the discrepancy between theory and observation for solar neutrinos is outside the range of uncertainties. Thus we have a real problem.

Experiments Are Required for Progress

The solar neutrino puzzle has been around for more than two decades. Many theoretical speculations have been advanced to try to solve its problem. There is no consensus on which, if any, of the suggested solutions is correct.

Clearly progress in solar neutrino research requires new experiments. Since there are a plethora of interesting theoretical explanations of the solar neutrino problem, new measurements are necessary to determine which solution *nature* has adopted. Observations must be made with different detectors and techniques in order to test theoretical predictions and to eliminate the possibility that systematic uncertainties influence the interpretations. After we review the ongoing experiments we have already mentioned, we will look at some of the most promising experiments now being prepared around the world.

The ^{37}Cl Experiment

The beautiful ^{37}Cl experiment of R. Davis Jr. and his collaborators was for two decades the only operating solar neutrino detector. The reaction that is used for the

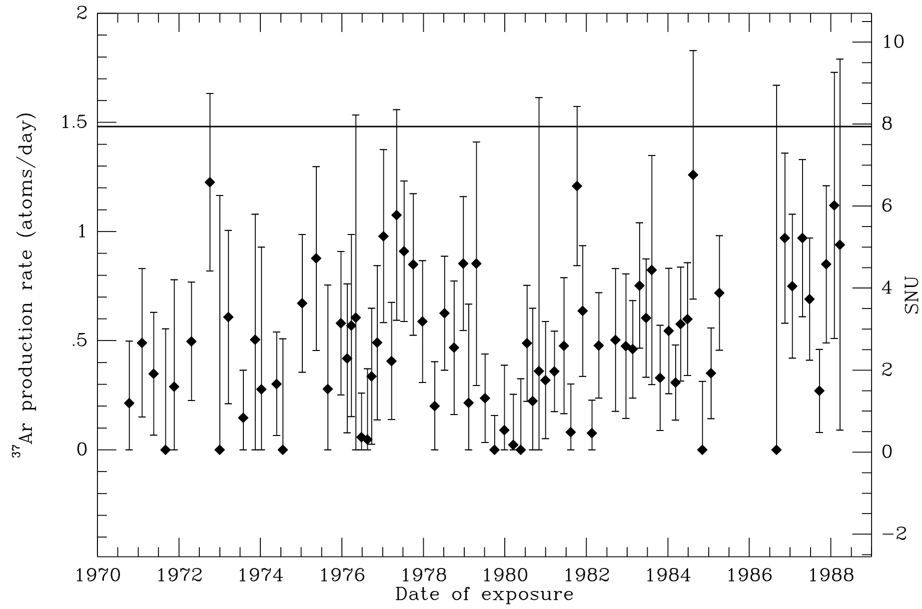


Figure 1. Observational results from the ^{37}Cl solar neutrino experiment. the line at 7.9 SNU across the top of the figure represents the prediction of the standard model. The gap in the observations in 1985-1986 was due to the failure of circulating pumps in the experimental setup. (From observations by Davis, Cleveland, and Rowley.)

detection of the neutrinos is:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar},$$

which has a threshold energy of 0.8 MeV. The target is a tank containing 100,000 gallons of C_2Cl_4 (perchloroethylene, a cleaning fluid), deep in the Homestake Gold Mine in Lead, South Dakota. (Recall that the underground location is necessary in order to avoid background events from cosmic rays.) Every few months, for about 15 years, Davis and his collaborators have extracted a small sample of ^{37}Ar, typically on the order of 15 atoms, out of the total of more than 10^{30} atoms in the tank. The ^{37}Ar produced in the tank is separated chemically from the C_2Cl_4, purified, and counted in low background proportional counters. The typical background counting rate for the counters corresponds to about one radioactive decay of an ^{37}Ar nucleus a month! Experiments have been performed to show that ^{37}Ar produced in the tank is extracted with more than 90% efficiency.

Figure 1 shows all the experimental data that have been reported by Davis, B. Cleveland, and K. Rowley. The average observed capture rate is:

$$\text{capture rate} = (2.1 \pm 0.3)\ \text{SNU}$$

a rate which is due to solar neutrinos having provided all of the significant contributions to the background. (It is interesting to note that the nine experiments made in 1986 to 1988 are two standard deviations (3.2 ± 0.7 SNU) higher than the average for 1970 - 1988.)

Table 3 shows the contribution to the total capture rate predicted by the combined standard model. Of the total eight SNU, about 75% (6 SNU) is contributed by the

Table 3:

Predicted capture rates for a ^{37}Cl detector.

Neutrino source	**Capture rate (SNU)**
pp	0.0
pep	0.2
hep	0.03
^{7}Be	1.1
^{8}B	6.1
^{13}N	0.1
^{15}O	0.3
^{17}F	0.003
Total	7.9 SNU

^{8}B neutrinos. The difference between the average measured value shown in Figure I and eight SNU (the dotted line) is "the solar neutrino problem."

The Kamiokande II Experiment

The Kamiokande II experiment. which is located in the Japanese Alps, detects *Cerenkov light*[5] emitted by electrons that are scattered by solar neutrinos. The reaction by which the neutrinos are observed is:

$$\nu + e \rightarrow \nu' + e' \ ,$$

where the "primes" on the outgoing particle symbols indicate that the momentum and energy of each particle can be changed by the scattering interactions. This is the first of several solar neutrino experiments that are planned or are in progress in which this neutrino-electron scattering process will be studied. For the higher-energy neutrinos (energies greater than 5 MeV, that is, ^{8}B and hep neutrinos only) that can be observed by this process using available techniques, the scattering provides additional information not available with a radio-chemical detector like the chlorine experiment. Neutrino-electron scattering experiments furnish information about the incident neutrino energy spectrum (from measurements of the recoil energies of the scattered electrons), determine the direction from which the neutrinos arrive, and record the precise time of each event.

The Kamiokande experiment was originally designed as a three kiloton underground water Cerenkov detector in order to try to detect the decay of protons, predicted by certain "grand unified theories" of physics. In late 1984, improvements were begun to make possible the detection of the relatively low-energy events that are expected to be produced by solar neutrinos. This detector also provided (together with the IMB detector, a water Cerenkov detector located in a salt mine in Ohio) the first observation of neutrinos from Supernova 1987A: the supernova neutrinos happen to have energies in about the same range as those expected from solar rm^8B neutrinos. Fortunately, an upgrade of Kamiokande II to a full-time solar neutrino detector had been completed just a few months before the neutrinos from the supernova explosion (which occurred in a nearby galaxy, the Large Magellanic Cloud) reached the Earth.

The preliminary results from the Kamiokande II detector yield a ^{8}B neutrino flux that is approximately 0.45 of the standard model flux, statistically about 3-sigma away from zero and from the standard model value. A significant forward peaking of the recoil electrons is observed along the direction of the Earth-Sun axis. This confirming result is of great importance since all of the previous observational results on solar neutrinos came from a single ^{37}Cl experiment.

[5]Cerenkov radiation is given off when electrons move through a medium with a speed greater than the speed of light *in that medium*. In a sense, it is a "shock-wave" in light, analogous to the more familiar sonic boom we hear when an object moves through air faster than the speed of sound. – Ed.

A Geochemical Experiment

A geochemical experiment has been developed over the past several years at Los Alamos National Laboratory, in which neutrinos will be detected via their absorption by molybdenum atoms shielded from atmospheric phenomena by the covering of a deep mine. The absorption of neutrinos produces an unstable but long-lived isotope of the element technetium that would not be present in a steady state situation in which there were no high-energy solar neutrinos. The method uses the neutrino capture reaction:

$$\nu_e + {}^{98}\mathrm{Mo} \rightarrow {}^{98}\mathrm{Tc}^* + e^- \ .$$

Neutrino absorption produces a variety of excited nuclear states of technetium that can only be populated by the ^{8}B (and much less importantly, hep) neutrinos.

The ^{98}Tc has a mean life of 4.2 million years; hence, the present abundance reflects the average production rate during a period of several million years. The lifetime is too long for the isotope to be detected from its natural radioactivity: there are simply not enough atoms decaying at any given time for instruments that detect radio activity to measure. Instead, enough technetium is accumulated so that a sufficient number of atoms (roughly 10 million) are available for the ^{98}Tc to be counted by an ultra sensitive *mass-spectrometer* (an instrument that sorts out atoms by their mass). Thus this experiment will test the constancy of the flux of ^{8}B neutrinos over the past several million years.

Standard ideas about the time scale for the evolution of the Sun (estimated to be about 10 billion years) imply that the time-averaged flux of ^{8}B neutrinos measured with the ^{98}Mo experiment will be the same to within 1% (much less than the experimental uncertainties) as the contemporary flux determined from the ^{37}Cl and Kamiokande II detectors.

The experimentalists are using the Henderson molybdenum mine in Colorado, in which the ore is recovered at great depth (1500–1800 meters). The sources of background have been carefully evaluated and are believed to be sufficiently low to permit the observation of ^{98}Tc production from solar neutrinos.

Gallium Detectors

Two radiochemical solar neutrino experiments using the element gallium (^{71}Ga) are under way, one by a primarily Western European collaboration (GALLEX) and the second by a group which will work in the Soviet Union (Institute for Nuclear Research, Moscow). The GALLEX collaboration plans to use 30 tons of gallium in an aqueous solution; the detector will be located in the Gran Sasso Laboratory in Italy. The Soviet experiment will use about 60 tons of gallium metal as a detector in a solar neutrino laboratory constructed underneath a high mountain in the Baksan Valley in the Caucasus Mountains of the Soviet Union. The scale of both of these experiments is impressive considering that, at the time the experimental techniques were developed, the total world production of gallium was only 10 tons per year!

The gallium experiments can furnish unique and fundamental information about nuclear processes in the solar interior and about neutrino propagation. The neutrino absorption reaction is:

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow e^- + {}^{71}\mathrm{Ge} \ .$$

The germanium atoms are removed chemically from the gallium and the radioactive decays of ^{71}Ge (half-life 11.4 days) are measured in small proportional counters. The threshold for absorption of neutrinos by ^{71}Ga is 0.233 MeV, which is well below the maximum energy of the pp neutrinos. No other solar neutrino experiment has a demonstrated capability to detect the low-energy neutrinos from the basic pp reaction (reaction 1a of Table 1).

Table 4 shows the calculated contribution from individual neutrino sources to the predicted capture rate for the gallium reaction. Neutrinos from the basic pp reaction are expected, according to the standard model. to produce approximately half of the computed total capture rate. The other main contributors are ^{7}Be neutrinos, about one-quarter of the total rate, and ^{8}B neutrinos, about 10%.

Table 4:

Predicted capture rates for a ^{71}Ga detector.

Neutrino source	**Capture rate (SNU)**
pp	70.8
pep	3.0
hep	0.06
^{7}Be	34.3
^{8}B	14.0
^{13}N	3.8
^{15}O	6.1
^{17}F	0.06
Total	132^{+20}_{-17} SNU

The initial chemical extraction is different in the GALLEX and the Soviet experiments, but the final chemical procedures and the methods of low-level counting will be similar for both collaborations. The comparison of the results from the two experiments can provide a valuable check on any possible systematic errors. The GALLEX collaboration will employ gallium in the chemical form of an aqueous solution of gallium chloride and hydrochloric acid. The radioactive ^{71}Ge is removed from this solution by purging with gas. The GALLEX collaboration will use a single vessel to contain the gallium chloride solution. The extracted ^{71}Ge will be converted to germane (GeH_4) and measured in a miniature gas proportional detector. This group was hoping to receive their full amount of gallium by late 1989 and to begin measurements in 1990.

The Soviet experiment, with American collaborators, is sometimes referred to as SAGE (Soviet-American-Gallium-Experiment). The SAGE collaboration will use gallium metal as the target material. The germanium extraction process involves mixing the metal with a dilute hydrochloric acid solution. The ^{71}Ge is removed from the acidic solution by purging with gas collected in water, a procedure similar to the primary ^{71}Ge separation used in the gallium chloride process. The process used by the Soviet group is slower and more cumbersome, but is also capable of obtaining a high recovery yield. The ^{71}Ge radioactivity will be measured in small proportional counters similar to those developed for the ^{37}Cl experiment. The Soviet experimentalists have 60 tons of gallium available and began taking data in 1988. The current plan of the Soviet scientists and their U.S. collaborators is to present the first results of their observations at a neutrino conference in June 1990 in Geneva.

Scientists are eagerly anticipating the results of the gallium experiments because they may indicate which class of solution is correct for the solar neutrino problem, faulty astrophysics or new physics. Most "nonstandard" models of the Sun's interior still predict event rates that are not very different from the standard solar model. The minimum neutrino rate that is consistent with the assumption that the energy produced by nuclear fusion currently balances the energy lost through the Sun's luminosity is about 60% of the standard model value, provided that no physics beyond our current understanding of electrical or weak nuclear interactions affects the propagation of the neutrinos.

On the other hand, some explanations of the solar neutrino problem that involve new ideas in particle physics imply that the event rate in the gallium experiments will be much less than the standard model prediction, perhaps no more than 10% of the standard value.

The Next Decade

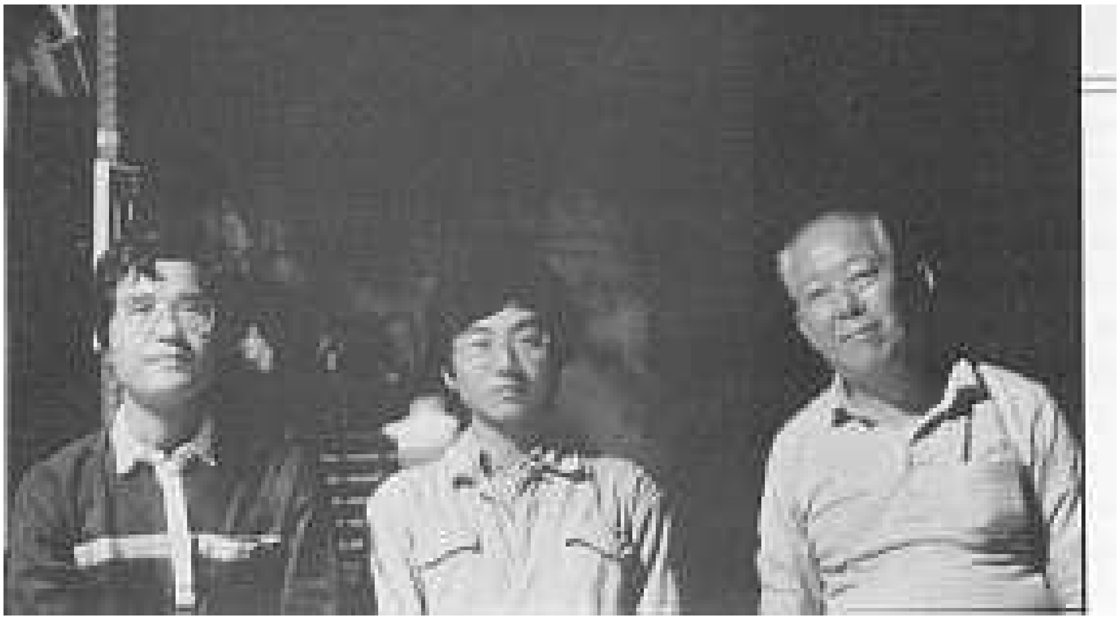
The first quarter century of solar neutrino astronomy has produced a well-defined "solar neutrino problem." Experiments to be performed in the next decade may reveal the solution to this problem and point us toward either a more complete theory of stellar energy generation or better ideas about neutrino propagation. If we are lucky, solar neutrino experiments might do both.

Editor's Note: Professor John Bahcall works at the Institute for Advanced Study at Princeton and chairs the Astronomy and Astrophysics Survey Committee of the National Academy of Sciences, which will set the priorities for astronomical research in the U.S. for the next decade. He is one of the leading astrophysicists in the world and has worked on galaxies, quasars, cosmology, neutron stars, and neutrinos from the Sun. In 1989, Cambridge University Press published a new monograph by Dr. Bahcall entitled *Neutrino Astrophysics,* which sets out the exploration of the cosmos using neutrinos for students and scientists. We asked if he would summarize the current situation concerning neutrinos from the Sun for *Mercury* readers and he very kindly obliged with this article.

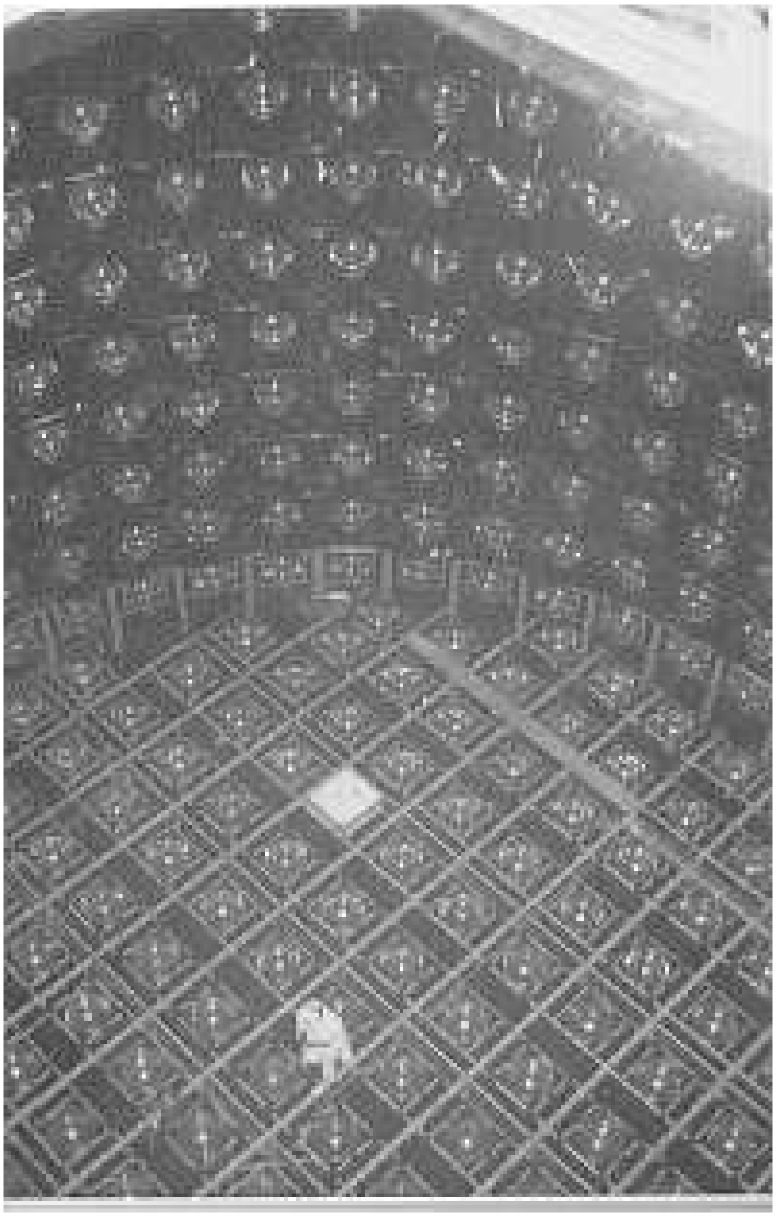
John Bahcall, professor at the Institute for Advanced Study, Princeton, NJ. He is very active in a number of areas in astronomy and is involved in the planning and operation of the Hubble Space Telescope. Currently, he is the president-elect of the American Astronomical Society. (Photograph courtesy of John Bahcall)

Shortly after the proposal in 1964 that a ^{37}Cl solar neutrino experiment was feasible, three of the people most involved were photographed in front of a small version of the chlorine tank. From right to left, they are: Raymond Davis, Jr., John Bahcall, and Don Harmer. (Photograph courtesy of Raymond Davis, Jr.)

Brookhaven Solar Neutrino Experiment. Ray Davis Jr. was the principal investigator for this first solar neutrino experiment located in the Homestake Gold Mine, Lead, South Dakota. The tank contains 100,000 gallons of perchloroethylene and is 4850 feet underground. Chlorine was chosen as the neutrino detector because its characteristics were favorable for building a relatively cheap but large detector. Ray Davis is leaning on the catwalk above the tank. (Photograph courtesy of Raymond Davis, Jr.)



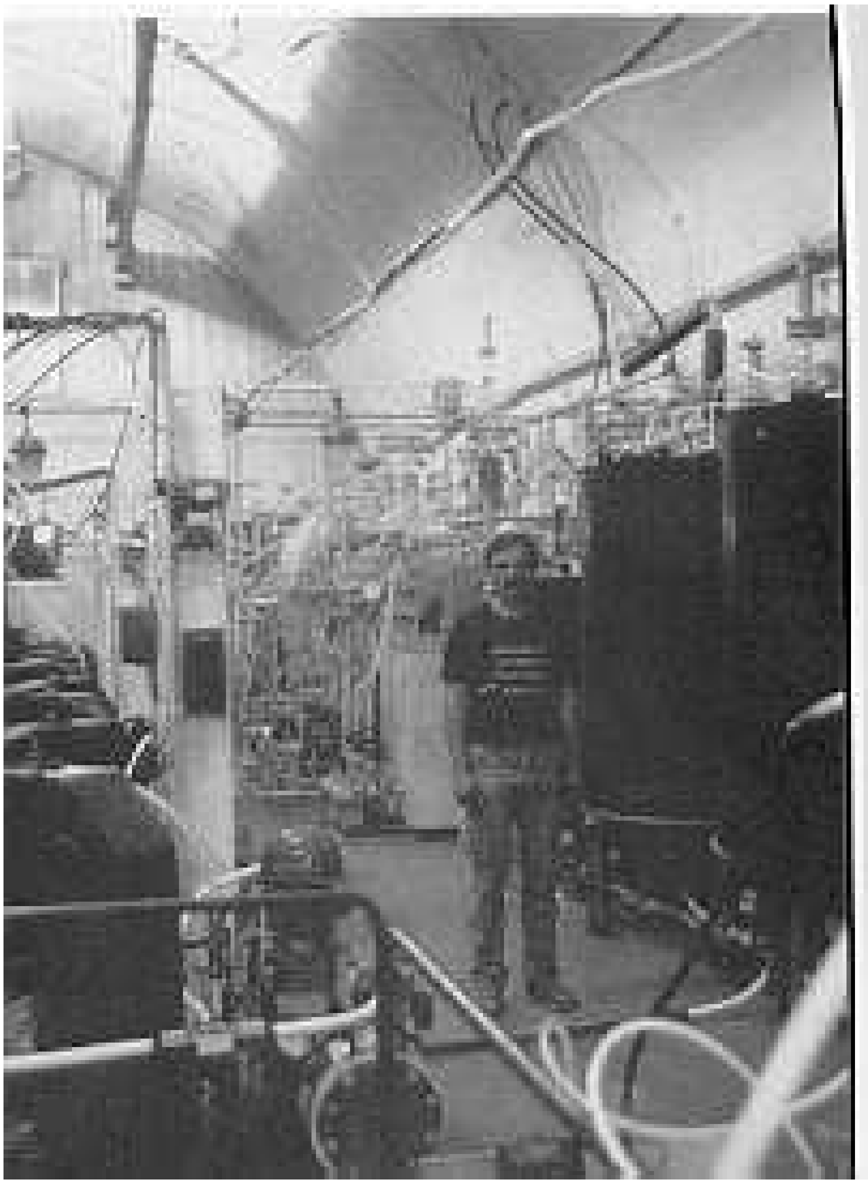
Three generations of Kamiokande neutrino experimentalists. From left to right: Y. Totsuka, N. Nakahato, and M. Koshiba. (Photograph courtesy of John Bahcall)



Kamiokande II solar neutrino experiment. This experiment is located 1000 meters underground in the Kamioka metal mine in the Japanese Alps. The detector is contained in a stell-walled cylindrical tank containing 3000 metric tons of water. 948 20-inch diameter photomultiplier tubes, to detect the Cerenkov light, uniformly line the inner surface of the tank. (Photograph courtesy of Y. Totsuka)

The GALLEX experimental buildings in the Gran Sasso Underground Physics Laboratory near L'Aquila, Central Italy. The front building is the target room where two gallium-chloride detector tanks are housed. The rear building contains the germanium detector spectrometer. (Photograph courtesy of T. Kirsten)

Three of the solar neutrino pioneers. From left to right: G. T. Zatsepin (founder of the Soviet solar neutrino experiment and honorary mayor of Neutrino City in the North Caucus region), John Bahcall, and Ray Davis, Jr., Leningrad, 1974. (Photograph courtesy of John Bahcall)



The underground Soviet-American (SAGE) solar neutrino collaboration. A Soviet scientist is standing in the center of the experimental setup, with the tanks containing the 60 tons of gallium metal on his left and the chemical extraction unit on hig right. (Photograph courtesy of John Wilkerson)