The Evolution of Neutrino Astronomy

John N. Bahcall

Institute for Advanced Study, Olden Lane, Princeton, NJ 08540

and

Raymond Davis, Jr.

Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104

How did neutrino astronomy evolve? Are there any useful lessons for astronomers and physicists embarking on new observational ventures today? We will answer the first question from our perspective. You, the reader, can decide for yourself whether there are any useful lessons.

The possibility of observing solar neutrinos began to be discussed seriously following the 1958 experimental discovery by Holmgren and Johnston that the cross section for production of the isotope ^{7}Be by the fusion reaction $^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$ was more than a thousand times larger than was previously believed. This result led Willy Fowler and Al Cameron to suggest that ^{8}B might be produced in the sun in sufficient quantities by the reaction $^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$ to produce an observable flux of high-energy neutrinos from ^{8}B beta-decay. Figure 1 shows the early evolution of neutrino astronomy as described in a viewgraph from a colloquium given by Ray at Brookhaven National Laboratory in 1971.

We begin our story in 1964, when we published back-to-back papers in Physical Review Letters arguing that a $100,000$ gallon detector of perchloroethylene could be built which would measure the solar neutrino capture rate on chlorine [1]. Our motivation was to use neutrinos to look into the interior of the sun and thereby test directly the theory of stellar evolution and nuclear energy generation in stars. The particular development that made us realize that the experiment could be done was the demonstration (by John in late 1963)

[1] We were asked to write a brief *Millennium Essay for the PASP* on the evolution of neutrino astronomy from our personal perspective. We present the way the history looks to us more than thirty-five years after our collaboration began and emphasize those aspects of the development of neutrino astronomy that may be of interest or of use to physicists and astrophysicists today. We stress that all history is incomplete and distorted by the passage of time and the fading of memories. For earlier more detailed reviews, the reader can consult two articles we wrote when the subject was still in its childhood and our memories were more immediate (Bahcall & Davis 1976, 1982). The interested reader can find references in these articles to the early works of Bethe, of Holmgren and Johnston, and of Fowler and Cameron and to the works of many other early pioneers in stellar fusion and stellar astrophysics.

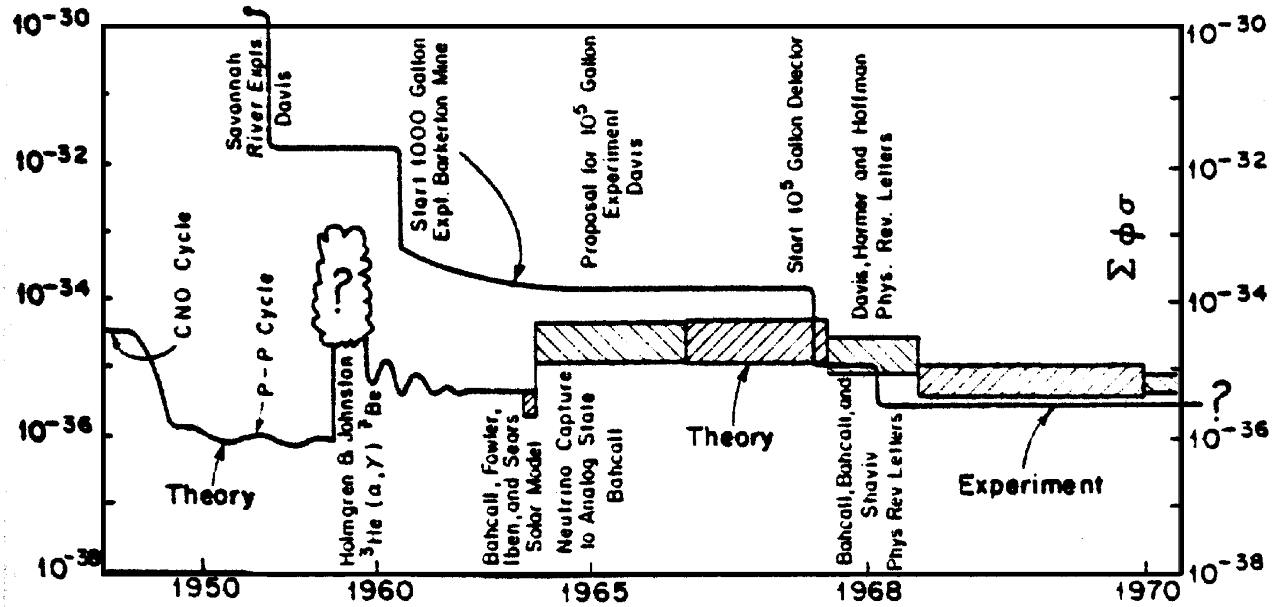

Fig. 1.— Some of the principal events in the early development of the solar neutrino problem. The experimental upper limit is indicated by the think black curve and the range of theoretical values by the cross-hatched region. The units are captures per target atom per second (10^{-36} capture/target atom/s = 1 SNU). (Viewgraph: R. Davis jr., circa 1971.)

that the principal neutrino absorption cross section on chlorine was twenty times larger than previously calculated due to a super-allowed nuclear transition to an excited state of argon.

If you have a good idea today, it likely will require many committees, many years, and many people in order to get the project from concept to observation. The situation was very different in 1964. Once the decision to go ahead was made, a very small team designed and built the experiment; the entire team consisted of Ray, Don Harmer (on leave from Georgia Tech), and John Galvin (a technician who worked part-time on the experiment). Kenneth Hoffman, a (then) young engineer provided expert advice on technical questions. The money came out of the chemistry budget at Brookhaven National Laboratory. Neither of us remember a formal proposal ever being written to a funding agency. The total capital expenditure to excavate the cavity in the Homestake Gold Mine in South Dakota, to build the tank, and to purchase the liquid was 0.6 million dollars (in 1965 dollars).

During the period 1964-1967, Fred Reines and his group worked on three solar neutrino experiments in which recoil electrons produced by neutrino interactions would be detected by observing the associated light in an organic scintillator. Two of the experiments, which exploited the elastic scattering of neutrinos by electrons, were actually performed and led to a (higher-than-predicted) upper limit on the ^{8}B solar neutrino flux. The third experiment, which was planned to detect neutrinos absorbed by ^{7}Li, was abandoned after the initial chlorine results showed that the solar neutrino flux was low. These three experiments introduced the technology of organic scintillators into the arena of solar neutrino research, a technique that will only finally be used in 2001 when the BOREXINO detector will begin to detect low energy solar neutrinos. Also during this period, John investigated the properties of neutrino electron scattering and showed that the forward peaking from ^{8}B neutrinos is large, a feature that was incorporated two and half decades later in the Kamiokande (and later SuperKamiokande) water Cherenkov detectors.

Ray Davis shows John Bahcall the tank containing 100,000 gallons of perchloroethylene. The picture was taken in the Homestake mine shortly before the experiment began operating.

The first results from the chlorine experiment were published in 1968, again in a back-to-back comparison (in PRL) between measurements and standard predictions. The initial results have been remarkably robust; the conflict between chlorine measurements and standard solar model predictions has lasted over three decades. The main improvement has been in the slow reduction of the uncertainties in both the experiment and the theory. The efficiency of the Homestake chlorine experiment was tested by recovering carrier solutions, by producing ^{37}Ar in the tank with neutron sources, and by recovering ^{36}Cl inserted in a tank of perchloroethylene. The solar model was verified by comparison with precise helioseismological measurements.

For more than two decades, the best-estimates for the observational and for the theoretical prediction have remained essentially constant. The discrepancy between the standard solar model prediction and the chlorine observation became widely known as "the solar neutrino problem."

Very few people worked on solar neutrinos during the period 1968-1988. The chlorine experiment was the only solar neutrino experiment to provide data in these two decades. It is not easy for us to explain why this was the case; we certainly tried hard to interest others in doing different experiments and we gave many joint presentations about what came to be known as "the solar neutrino problem". Each of us had one principal collaborator during this long period, Bruce Cleveland (experimental) and Roger Ulrich (solar models). A large effort to develop a chlorine experiment in the Soviet Union was led by George Zatsepin, but it was delayed by the practical difficulties of creating a suitable underground site for the detector. Eventually, the effort was converted into a successful gallium detector, SAGE, led by Vladimir Gavrin and Tom Bowles, that gave its first results in 1990.

Only one year after the first (1968) chlorine results were published, Vladimir Gribov and Bruno Pontecorvo proposed that the explanation of the solar neutrino problem was that neutrinos oscillated between the state in which they were created and a more difficult to detect state. This explanation, which is the consensus view today, was widely disbelieved by nearly all of the particle physicists we talked to in those days. In the form in which solar neutrino oscillations were originally proposed by Gribov and Pontecorvo, the process required that the mixing angles between neutrino states be much larger than the quark mixing angles, something which most theoretical physicists believed, at that time, was unlikely. Ironically, a flood of particle theory papers explained, more or less 'naturally', the large neutrino mixing angle that was decisively demonstrated thirty years later in the SuperKamiokande atmospheric neutrino experiment.

One of the most crucial events for early solar neutrino research occurred in 1968 while we were relaxing in the sun after a swim at the CalTech pool. Gordon Garmire (now a PI for the Chandra X-ray satellite) came up to Ray, introduced himself, and said he had heard about the chlorine experiment. He suggested to Ray that it might be possible to reduce significantly the background by using pulse rise time discrimination, a technique used for proportional counters in space experiments. The desired fast-rising pulses from ^{37}Ar Auger electrons are different from the slower rising pulses from a background gamma or cosmic ray. Ray went back to Brookhaven and asked the local electronic experts if it would be possible to implement this technique for the very small counters he used. The initial answer was that the available amplifiers were not fast enough to be used for this purpose with the small solar neutrino counters. But, in about a year three first class electronic engineers at BNL, Veljko

Radeca, Bob Chase, and Lee Rogers were able to build electronics fast enough to be used to measure the rise time in Ray's counters.

This 'swimming-pool' improvement was crucial for the success of the chlorine experiment and the subsequent radio-chemical gallium solar neutrino experiments, SAGE, GALLEX, and GNO. Measurements of the rise-time as well as the pulse energy greatly reduce the background for radio-chemical experiments. The backgrounds can be as low as one event in three months.

In 1978, after a decade of disagreement between the Homestake neutrino experiment and standard solar model predictions, it was clear to everyone that the subject had reached an impasse and a new experiment was required. The chlorine experiment is, according to standard solar model predictions, sensitive primarily to neutrinos from a rare fusion reaction that involves ^{8}B neutrinos. These neutrinos are produced in only 2 of every 10^4 terminations of the basic *pp* fusion chain. In the early part of 1978, there was a conference of interested scientists who got together at Brookhaven to discuss what to do next. The consensus decision was that we needed an experiment that was sensitive to the low energy neutrinos from the fundamental *pp* reaction.

The only remotely-practical possibility appeared to be another radiochemical experiment, this time with ^{71}Ga (instead of ^{37}Cl) as the target. But, a gallium experiment (originaly proposed by the Russian theorist V. A. Kuzmin in 1965) was expensive; we needed about three times the world's annual production of gallium to do a useful experiment. In an effort to generate enthusiasm for a gallium experiment, we wrote another Physical Review Letters paper, this time with a number of interested experimental colleagues. We argued that a gallium detector was feasible and that a gallium measurement, which would be sensitive to the fundamental $p-p$ neutrinos, would distinguish between broad classes of explanations for the discrepancy between prediction and observation in the ^{37}Cl experiment. Over the next five or six years, the idea was reviewed a number of times in the United States, always very favorably. DOE appointed a blue ribbon panel headed by Glen Seaborg that endorsed enthusiastically both the experimental proposal and the theoretical justification.

To our great frustration and disappointment, the gallium experiment was never funded in the United States, although the experimental ideas that gave rise to the Russian experiment (SAGE) and the German-French-Italian-Israeli-US experiment (GALLEX) largely originated at Brookhaven. Physicists strongly supported the experiment and said the money should come out of an astronomy budget; astronomers said it was great physics and should be supported by the physicists. DOE could not get the nuclear physics and the particle physics sections to agree on who had the financial responsibility for the experiment. In a desperate effort to break the deadlock, John was even the PI of a largely Brookhaven proposal to the NSF (which did not support proposals from DOE laboratories).A pilot experiment was performed with 1.3 tons of gallium by an international collaboration (Brookhaven, University of Pennsylvania, MPI, Heidelberg, IAS, Princeton, and the Weizmann Institute) which developed the extraction scheme and the counters eventually used in the GALLEX full scale experiment.

In strong contrast to what happened in the United States, Moissey Markov, the Head of the Nuclear Physics Division of the Russian Academy of Sciences, helped establish a neutrino laboratory within the Institute for Nuclear Research, participated in the founding of the Baksan neutrino observatory , and was instrumental in securing 60 tons of gallium free to Russian scientists for the duration of a solar neutirno experiment.

The Russian-American gallium experiment (SAGE) went ahead under the leadership of Vladimir Gavrin, George Zatsepin (Institute for Nuclear Research, Russia), and Tom Bowles (Los Alamos) and the mostly European experiment (GALLEX) was led by Till Kirsten (Max Planck Institute, Germany). Both experiments had a strong but not primary US participation.

The two gallium experiments were performed in the decade of the 1990's and gave very similar results, providing the first experimental indication of the presence of $p-p$ neutrinos. Both experiments were tested by measuring the neutrino rate from an intense laboratory radioactive source.

There were two dramatic developments in the solar neutrino saga, one theoretical and one experimental, before the gallium experiments produced observational results. In 1985, two Russian physicists proposed an imaginative solution of the solar neutrino problem that built upon the earlier work of Gribov and Pontecorvo and, more directly, the insightful investigation by Lincoln Wolfenstein (of Carnegie Mellon). Stanislav Mikheyev and Alexei Smirnov showed that, if neutrinos have masses in a relatively wide range, then a resonance phenomenon in matter (now universally known as the MSW effect) could convert efficiently many of the electron-type neutrinos created in the interior of the sun to more difficult to detect muon and tau neutrinos. The MSW effect can work for small or large neutrino mixing angles. Because of the elegance of the theory and the possibility of explaining the experimental results with small mixing angles (analogous to what happens in the quark sector), physicists immediately began to be more sympathetic to particle physics solutions to the solar neutrino problem. More importantly, they became enthusiasts for new solar neutrino experiments.

The next big break-through also came from an unanticipated direction. The Kamiokande water Cherenkov detector was developed to study proton decay in a mine in the Japanese

Alps; it set an important lower limit on the proton lifetime. In the late 1980's, the detector was converted by its Japanese founders, Masatoshi Koshiba and Yoji Totsuka, together with some American colleagues (Gene Beier and Al Mann of the U. of Pennsylvania) to be sensitive to the lower energy events expected from solar neutrinos. With incredible foresight, these experimentalists completed in late 1986 their revisions to make the detector sensitive to solar neutrinos, just in time to observe the neutrinos from Supernova 1987a emitted in the LMC 170,000 years earlier. (Supernova and solar neutrinos have similar energies, ~ 10 MeV, much less than the energies that are relevant for proton decay.) In 1996, a much larger water Cherenkov detector (with 50,000 tons of pure water) began operating in Japan under the leadership of Yoji Totsuka, Kenzo Nakamura, Yoichiro Suzuki (from Japan) , and Jim Stone and Hank Sobel (from the United States).

So far, five experiments have detected solar neutrinos in approximately the numbers (within a factor of two or three) and in the energy range (< 15 MeV) predicted by the standard solar model. This is a remarkable achievement for solar theory since the ^{8}B neutrinos that are observed primarily in three of these experiments (chlorine, Kamiokande, and its successor SuperKamiokande) depend upon approximately the 25th power of the central temperature. The same set of nuclear fusion reactions that are hypothesized to produce the solar luminosity also give rise to solar neutrinos. Therefore, these experiments establish empirically that the sun shines by nuclear fusion reactions among light elements in essentially the way described by solar models.

Nevertheless, all of the experiments disagree quantitatively with the combined predictions of the standard solar model and the standard theory of electroweak interactions (which implies that nothing much happens to the neutrinos after they are created). The disagreements are such that they appear to require some new physics that changes the energy spectrum of the neutrinos from different fusion sources.

Solar neutrino research today is very different from what it was three decades ago. The primary goal now is to understand the neutrino physics, which is a prerequisite for making more accurate tests of the neutrino predictions of solar models. Solar neutrino experiments today are all large international collaborations, each typically involving of order 10^2 physicists. Nearly all of the new experiments are electronic, not radiochemical, and the latest generation of experiments measure typically several thousand events per year (with reasonable energy resolution), compared to rates that were typically 25 to 50 per year for the radiochemical experiments (which have no energy resolution, only an energy threshold). Solar neutrino experiments are currently being carried out in Japan (SuperKamiokande, in the Japanese Alps), in Canada (SNO, which uses a kiloton of heavy water in Sudbury, Ontario), in Italy (BOREXINO, ICARUS, and GNO, each sensitive to a different energy range and all operating in the Gran Sasso Underground Laboratory), in Russia (SAGE, in the Caucasus region), and in the United States (Homestake chlorine experiment). The SAGE, chlorine, and GNO experiments are radiochemical; the others are electronic.

Since 1985, the chlorine experiment has been operated by the University of Pennsylvania under the joint leadership of Ken Lande and Ray Davis. Lande and Paul Wildenhain have introduced major improvements in the extraction and measurement systems, making the chlorine experiment a valuable source of new precision data.

The most challenging and important frontier for solar neutrino research is to develop experiments that can measure the energies of individual low-energy neutrinos from the basic *pp* reaction, which constitutes (we believe) more than 90% of the solar neutrino flux.

Solar neutrino research is a community activity. Hundreds of experimentalists have collaborated to carry out difficult, beautiful measurements of the elusive neutrinos. Hundreds of other researchers helped refine the solar model predictions, measuring accurate nuclear and solar parameters and calculating input data such as opacities and equation of state.

Three people played special roles. Hans Bethe was the architect of the theory of nuclear fusion reactions in stars, as well as our mentor and hero. Willy Fowler was a powerful and enthusiastic supporter of each new step and his keen physical insight motivated much of what was done in solar neutrino research. Bruno Pontecorvo opened everyone's eyes with his original insights, including his early discussion of the advantages of using chlorine as a neutrino detector and his suggestion that neutrino oscillations might be important.

In the next decade, neutrino astronomy will move beyond our cosmic neighborhood and, we hope, will detect distant sources. The most likely candidates now appear to be gamma-ray bursts. If the standard fireball picture is correct and if gamma-ray bursts produce the observed highest-energy cosmic rays, then very high energy (10^{15} eV) neutrinos should be observable with a km^2 detector. Experiments with the capability to detect neutrinos from gamma-ray bursts are being developed at the South Pole (AMANDA and ICECUBE), in the Mediterranean Sea (ANTARES, NESTOR) and even in space.

Looking back on the beginnings of solar neutrino astronomy, one lesson appears clear to us: if you can measure something new with reasonable accuracy, then you have a chance to discover something important. The history of astronomy shows that very likely what you will discover is not what you were looking for. It helps to be lucky.

REFERENCES

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