OBSERVATIONAL NEUTRINO ASTROPHYSICS

J. N. BAHCALL

Institute for Advanced Study, Princeton, NJ 08540, USA
E-mail: jnb@sns.ias.edu

Abstract

I summarize the current state of observational neutrino astrophysics.

1 Introduction

The organizers of this conference asked me to review progress in the subject of observational neutrino astrophysics since the first Inner Space/Outer Space workshop in 1984 and then to summarize in more detail the current state of solar neutrino research.

Before doing that, I would like to say a few words about David Schramm, who inspired and stimulated me and so many of the people who are participating in this workshop.

David Schramm permanently changed the fields of particle physics and of cosmology. Physicists, after David, who think about new particles have to consider the cosmological implications of the particles they invent and astrophysicists who study large-scale structures have to take into account the probability that much of what is observed is due to the action of dark particles.

David made important scientific contributions with a spirit of infectious enthusiasm and with a sense of fun. He proved by his life that charm is a quantum number that applies to rare people and not just to rare particles.

The principle of conservation of energy did not apply to David. He had unlimited energy and he made important contributions to nearly all the problems of particle astrophysics, including solar neutrinos.

In 1984, at the time of the first Inner Space/Outer Space workshop, David was enthusiastically leading research in particle astrophysics in many different directions, theoretical and experimental. It is interesting to read the proceedings of that conference.[1] We had observed, in 1984, 0 supernova neutrinos, there was no ‘atmospheric anomaly’ (as atmospheric neutrino oscillations were described for the first decade or so), there was only 1 solar neutrino problem (the chlorine experiment versus the standard model prediction of the rate), and there was no realistic theoretical expectation that extragalactic neutrinos would be observed.

The situation is entirely different in 1999! The neutrinos from Supernova 1987a have been observed. These neutrinos provide unique and crucial information on both the astrophysics of supernova explosions and unique constraints on fundamental physics, including properties of neutrinos and tests of special relativity and the weak equivalence principle. There are now 5 operating solar neutrino experiments, each of which reports a deficit of neutrinos relative to the standard model, and SuperKamiokande and SNO are probing precise solar model independent tests of electroweak theory. Finally, we have a prediction of a measurable flux of extragalactic high-energy neutrinos from gamma-ray bursts (GRBs) that is based upon a conventional interpretation of photon observations.

2 Sources for which good luck is required

The cosmological mass density in the form of neutrinos with mass m_ν can be written in terms of the Hubble constant, H_0 (expressed in km/s/Mpc) as

$$\Omega_\nu \; = \; \left(\frac{50}{H_0}\right)^2 \left(\frac{m_\nu}{24\mathrm{eV}}\right)^2 \; \geq \; 0.002. \tag{1}$$

I have used the result from the SuperKamiokande atmospheric neutrino experiment to place a lower limit on Ω_ν. If there is a near degeneracy in neutrino masses, then the existing data are also consistent with a larger value of Ω_ν, perhaps even one that is cosmologically significant. In my view, we would have to be extremely lucky for such a near degeneracy to occur in Nature. On aesthetic grounds, and by analogy with other particles in the quark and lepton sectors, it does not seem very likely, but it is not impossible.

The result stated in Eq. (1) seems at first glance not to be very important. Actually, it is extremely important. Neutrinos are dark matter. The discovery of neutrino oscillations has provided the first direct evidence for particle dark matter !

There are a number of experiments that are now capable of observing neutrinos from nearby supernova, including all of the currently operating solar neutrino experiments. But, we will have to be lucky to observe one within the lifetime of the senior physicists participating in this workshop. The estimated rate of Galactic supernova ranges from an optimistic 10 per century to a relatively pessimistic 1 per century. It is important to be ready, but observing supernova neutrinos is not an appropriate subject for a graduate student thesis.

Finally, I want to mention the possibility of observing neutrinos from relic supernovae. Unfortunately, the theoretical estimates suggest that this is not currently a practical possibility. The most thorough calculations (by Totani, Sato, and Yoshi and by Woosley, Wilson, and Mayle in 1996) indicate that SuperKamiokande should detect only $\sim$ one relic supernova neutrino per year in a region free of solar neutrino background.

3 Solar neutrinos: an introduction

Figure 1 shows the sensitivity of different neutrino experiments plotted in the conventional plane of Events per year versus L/E (source-detector distance divided by neutrino energy). The quantity L/E measures the proper time in the rest frame and is therefore the appropriate quantity to use in determining how long a rare event (like vacuum oscillations) has to occur. It is clear from Fig. 1 that solar neutrino experiments provide an improvement in sensitivity (L/E) of about seven to nine orders of magnitude over the laboratory experiments that are shown. In addition, solar neutrinos allow one to study directly the nuclear reactions that cause the sun to shine.

I will discuss predictions of the combined standard model in the main part of this review. By ‘combined’ standard model, I mean the predictions of the standard solar model and the predictions of the minimal electroweak theory. We need a solar model to tell us how many neutrinos of what energy are produced in the sun and we need electroweak theory to tell us how the number and flavor content of the neutrinos are changed as they make their way from the center of the sun to detectors on earth. For all practical purposes, standard electroweak theory states that nothing happens to solar neutrinos after they are created in the deep interior of the sun.

Using standard electroweak theory and fluxes from the standard solar model, one can calculate the rates of neutrino interactions in different terrestrial detectors with a variety of energy sensitivities. The combined standard model also predicts that the energy spectrum from a given neutrino source

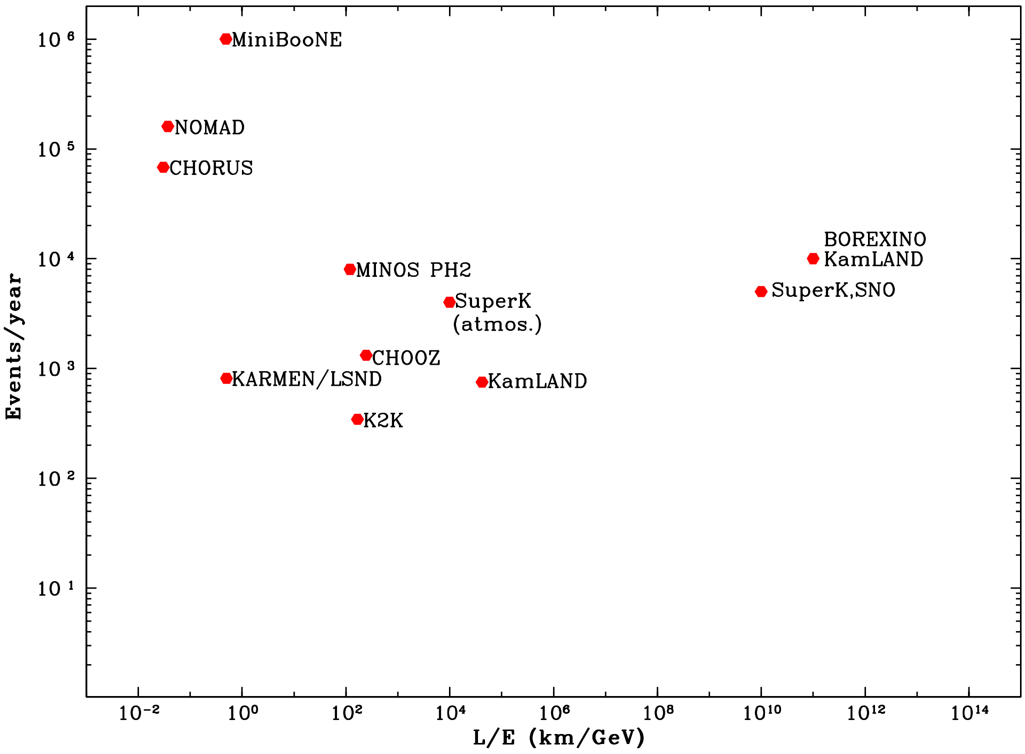

Figure 1: Neutrino oscillation experiments. The figure shows different neutrino oscillation experiments in a plane that reflects two of the important parameters that determine the sensitivity of an oscillation experiment, namely, the source-detector distance divided by the energy (L/E) and the number of neutrino events per year.

should be the same for neutrinos produced in terrestrial laboratories and in the sun and that there should not be measurable time-dependences (other than the seasonal dependence caused by the earth's orbit around the sun). The spectral and temporal departures from standard model expectations constitute 'smoking-gun' indications of new physics, but are expected to be small in all currently operating experiments and have not yet yielded definitive results. Therefore, I will concentrate here on inferences that can be drawn by comparing the total rates observed in solar neutrino experiments with the combined standard model predictions.

If you want to obtain numerical data or subroutines that are discussed in this talk, or to see relevant background information, you can copy them from my Web site: http://www.sns.ias.edu/∼jnb .

4 Standard Model Predictions

Figure 2 shows the predicted standard model neutrino fluxes from the dominant *p*-*p* fusion chain.

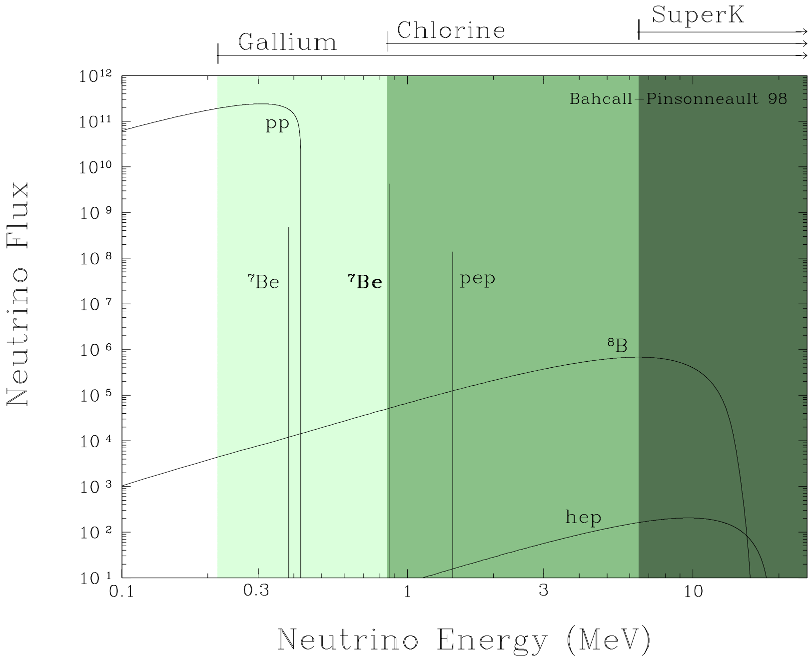

Figure 2: The energy spectrum of neutrinos from the *pp* chain of interactions in the Sun, as predicted by the standard solar model. Neutrino fluxes from continuum sources (such as *pp* and 8^B) are given in the units of counts per cm^2 per second. The *pp* chain is responsible for more than 98% of the energy generation in the standard solar model. Neutrinos produced in the carbon-nitrogen-oxygen CNO chain are not important energetically and are difficult to detect experimentally. The arrows at the top of the figure indicate the energy thresholds for the ongoing neutrino experiments.

Figure 3 shows for the chlorine experiment all the predicted rates and the estimated uncertainties (1σ) published by my colleagues and myself since

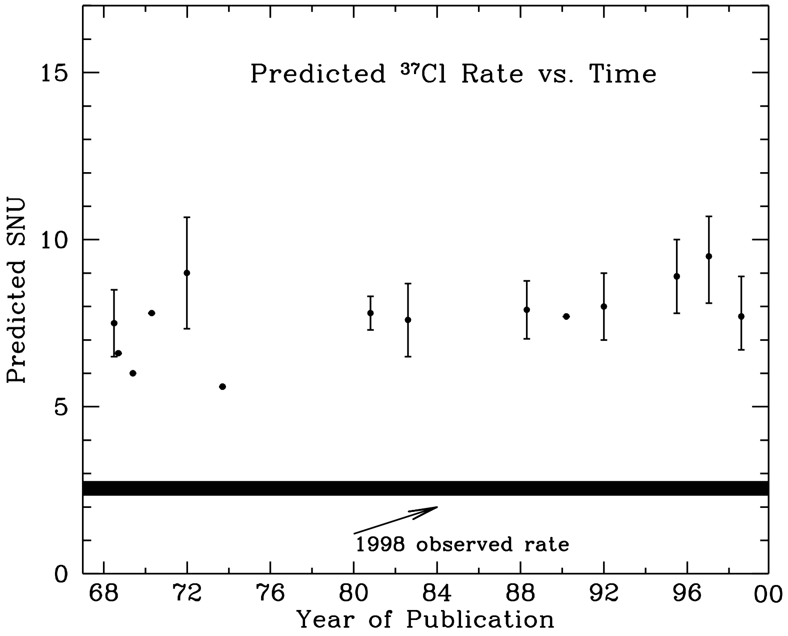

Figure 3: The predictions of John Bahcall and his collaborators of neutrino capture rates in the ^{37}Cl experiment are shown as a function of the date of publication (since the first experimental report in 1968). The event rate SNU is a convenient product of neutrino flux times interaction cross section, 10^{-36} interactions per target atom per sec. The predictions have been updated through 1998.

the first measurement by Ray Davis and his colleagues in 1968. This figure should give you some feeling for the robustness of the solar model calculations. Many hundreds and probably thousands of researchers have, over three decades, made great improvements in the input data for the solar models, including nuclear cross sections, neutrino cross sections, measured element abundances on the surface of the sun, the solar luminosity, the stellar radiative opacity, and the stellar equation of state. Nevertheless, the most accurate predictions of today are essentially the same as they were in 1968 (although now they can be made with much greater confidence). For the gallium experiments, the neutrino fluxes predicted by standard solar models, corrected for diffusion, have been in the range 120 SNU to 141 SNU since 1968. A SNU is a convenient unit with which to describe the measured rates of solar neutrino experiments: 10^{-36} interactions per target atom per second.

There are three reasons that the theoretical calculations of neutrino fluxes are robust: 1) the availability of precision measurements and precision calculations of input data; 2) the fact that the neutrino fluxes are produced by the same set of nuclear fusion reactions that are responsible for the precisely-measured solar luminosity; and 3) the precise agreement between the standard model predictions and the helioseismologically determined sound speeds. I will say a bit more about the helioseismology after reviewing the three solar neutrino problems associated with the measured total solar neutrino event rates.

5 Three Solar Neutrino Problems

I will now compare the predictions of the combined standard model with the results of the operating solar neutrino experiments. We will see that this comparison leads to three different discrepancies between the calculations and the observations, which I will refer to as the three solar neutrino problems.

Figure 4 shows the measured and the calculated event rates in the five ongoing solar neutrino experiments. This figure reveals three discrepancies between the experimental results and the expectations based upon the combined standard model. As we shall see, only the first of these discrepancies depends in an important way upon the predictions of the standard solar model.

5.1 Calculated versus Observed Absolute Rate

The first solar neutrino experiment to be performed was the chlorine radiochemical experiment, which detects electron-type neutrinos that are more energetic than 0.81 MeV. After more than a quarter of a century of operation of this experiment, the measured event rate is 2.56 ± 0.23 SNU, which is a factor of three less than is predicted by the most detailed theoretical calculations, $7.7^{+1.2}_{-1.0}$ SNU. Most of the predicted rate in the chlorine experiment is from the rare, high-energy ^{8}B neutrinos, although the ^{7}Be neutrinos are also expected to contribute significantly. According to standard model calculations, the *pep* neutrinos and the CNO neutrinos (for simplicity not discussed here) are expected to contribute less than 1 SNU to the total event

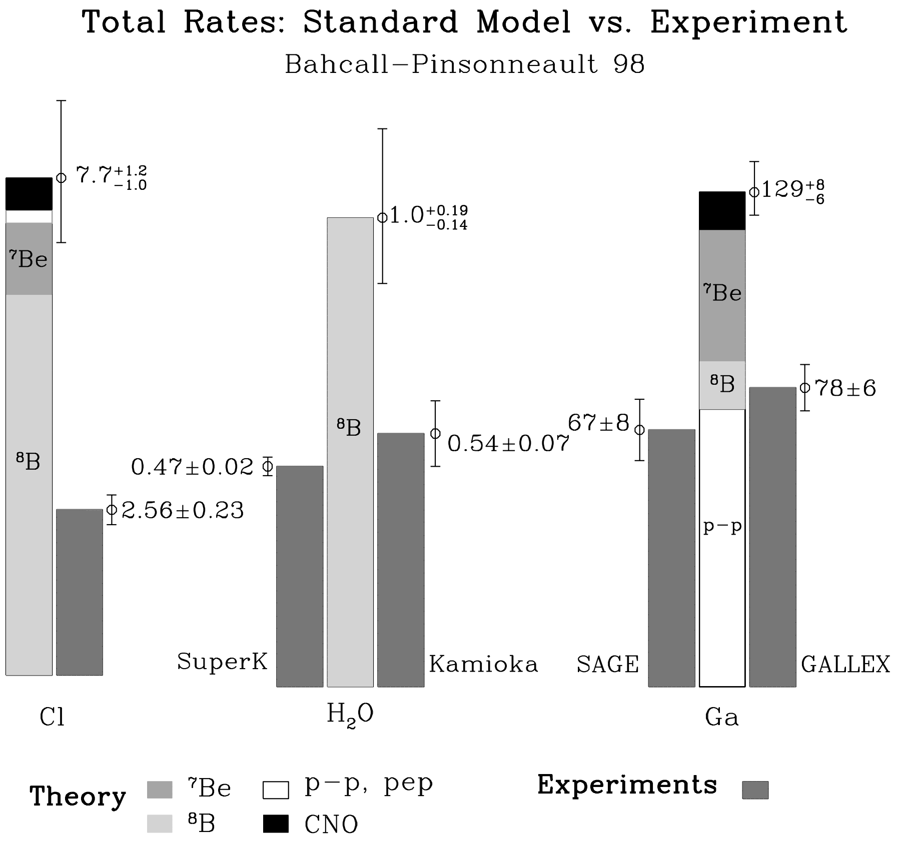

Figure 4: Comparison of measured rates and standard-model predictions for five solar neutrino experiments, The unit for the radiochemical experiments (chlorine and gallium) is a SNU; the unit for the water-Cerenkov experiments (Kamiokande and SuperKamiokande) is the rate predicted by the standard solar model plus standard electroweak theory.

rate.

This discrepancy between the calculations and the observations for the chlorine experiment was, for more than two decades, the only solar neutrino problem. I shall refer to the chlorine disagreement as the “first” solar neutrino problem.

5.2 Incompatibility of Chlorine and Water Experiments

The second solar neutrino problem results from a comparison of the measured event rates in the chlorine experiment and in the Japanese pure-water experiments, Kamiokande and SuperKamiokande. The water experiments detect higher-energy neutrinos, most easily above 7 MeV, by observing the Cerenkov radiation from neutrino-electron scattering: $\nu \ + \ e \ \longrightarrow \nu' \ + \ e'$. According to the standard solar model, ^{8}B beta decay, and possibly the much rarer but somewhat more energetic *hep* reaction, are the only important source of these higher-energy neutrinos.

The Kamiokande and SuperKamiokande experiments show that the observed neutrinos come from the sun. The electrons that are scattered by the incoming neutrinos recoil predominantly in the direction of the sun-earth vector; the relativistic electrons are observed by the Cerenkov radiation they produce in the water detector. In addition, the water Cerenkov experiments measure the energies of individual scattered electrons and therefore provide information about the energy spectrum of the incident solar neutrinos.

The total event rate in the water experiments, about 0.5 the standard model value (see Fig. 4), is determined by the same high-energy ^{8}B neutrinos that are expected, on the basis of the combined standard model, to dominate the event rate in the chlorine experiment. I have shown elsewhere that solar physics changes the shape of the ^{8}B neutrino spectrum by less than 1 part in 10^5. Therefore, we can calculate the rate in the chlorine experiment (threshold 0.8 MeV) that is produced by the ^{8}B neutrinos observed in the Kamiokande and SuperKamiokande experiments at an order of magnitude higher energy threshold.

If no new physics changes the shape of the ^{8}B neutrino energy spectrum, the chlorine rate from ^{8}B alone is 2.8 ± 0.1 SNU for the SuperKamiokande normalization (3.2 ± 0.4 SNU for the Kamiokande normalization), which exceeds the total observed chlorine rate of 2.56 ± 0.23 SNU.

Comparing the rates of the SuperKamiokande and the chlorine experiments, one finds—assuming that the shape of the energy spectrum of ^{8}B ν_e's is not changed by new physics—that the net contribution to the chlorine experiment from the *pep*, ^{7}Be, and CNO neutrino sources is negative: -0.2 ± 0.3 SNU. The contributions from the *pep*, ^{7}Be, and CNO neutrinos would appear to be completely missing; the standard model prediction for the combined contribution of *pep*, ^{7}Be, and CNO neutrinos is a relatively large 1.8 SNU. On the other hand, we know that the ^{7}Be neutrinos must be created in the sun since they are produced by electron capture on the same isotope (^{7}Be) which gives rise to the ^{8}B neutrinos by proton capture.

Hans Bethe and I pointed out shortly after the Kamiokande results first became available that this apparent incompatibility of the chlorine and water-Cerenkov experiments constitutes a "second" solar neutrino problem that is almost independent of the absolute rates predicted by solar models. The inference that is usually made from this comparison is that the energy spectrum of ^{8}B neutrinos is changed from the standard shape by physics not included in the simplest version of the standard electroweak model.

5.3 Gallium Experiments: No Room for ^{7}Be Neutrinos

The results of the gallium experiments, GALLEX and SAGE, constitute the third solar neutrino problem. The average observed rate in these two experiments is 73 ± 5 SNU, which is accounted for in the standard model by the theoretical rate of 72.4 SNU that is calculated to come from the basic *p-p* and *pep* neutrinos (with only a 1% uncertainty in the standard solar model *p-p* flux). The ^{8}B neutrinos, which are observed above 6.5 MeV in the Kamiokande experiment, must also contribute to the gallium event rate. Using the standard shape for the spectrum of ^{8}B neutrinos and normalizing to the rate observed in Kamiokande, ^{8}B contributes another 6 SNU. Given the measured rates in the gallium experiments, there is no room for the additional 34 ± 3 SNU that is expected from ^{7}Be neutrinos on the basis of standard solar models.

The seeming exclusion of everything but *p-p* neutrinos in the gallium experiments is the "third" solar neutrino problem. This problem is essentially independent of the previously-discussed solar neutrino problems, since it depends strongly upon the *p-p* neutrinos that are not observed in the other experiments and whose theoretical flux can be calculated accurately.

The missing ^{7}Be neutrinos cannot be explained away by a change in solar physics. The ^{8}B neutrinos that are observed in the Kamiokande experiment are produced in competition with the missing ^{7}Be neutrinos; the competition is between electron capture on ^{7}Be versus proton capture on ^{7}Be. Solar model explanations that reduce the predicted ^{7}Be flux generically reduce much more (too much) the predictions for the observed ^{8}B flux.

I conclude that either: 1) at least three of the five operating solar neutrino experiments (the two gallium experiments plus either chlorine or the two water Cerenkov experiments, Kamiokande and SuperKamiokande) have yielded misleading results, or 2) physics beyond the standard electroweak model is required to change the energy spectrum of ν_e after the neutrinos are produced in the center of the sun.

6 How Large an Uncertainty Does Helioseismology Suggest?

Could the solar model calculations be wrong by enough to explain the discrepancies between predictions and measurements for solar neutrino experiments? Helioseismology, which confirms predictions of the standard solar model to high precision, suggests that the answer is probably "No."

Figure 5 shows the fractional differences between the most accurate available sound speeds measured by helioseismology and sound speeds calculated with our best solar model (with no free parameters). The horizontal line corresponds to the hypothetical case in which the model predictions exactly match the observed values. The rms fractional difference between the calculated and the measured sound speeds is 1.1×10^{-3} for the entire region over which the sound speeds are measured, $0.05R_\odot < R < 0.95R_\odot$. In the solar core, $0.05R_\odot < R < 0.25R_\odot$ (in which about 95% of the solar energy and neutrino flux is produced in a standard model), the rms fractional difference between measured and calculated sound speeds is 0.7×10^{-3}.

If solar physics were responsible for the solar neutrino problems, how large would one expect the discrepancies to be between solar model predictions and helioseismological observations? The characteristic size of the discrepancies can be estimated using the results of the neutrino experiments and scaling laws for neutrino fluxes and sound speeds.

All recently published solar models predict essentially the same fluxes from the fundamental *pp* and *pep* reactions (amounting to 72.4 SNU in gallium experiments), which are closely related to the solar luminosity. Comparing the measured gallium rates and the standard predicted rate for the gallium experiments, the ^{7}Be flux must be reduced by a factor N if the disagreement is not to exceed n standard deviations, where N and n satisfy $72.4 + (34.4)/N = 72.2 + n\sigma$. For a 1σ disagreement, $N = 6.1$. Sound

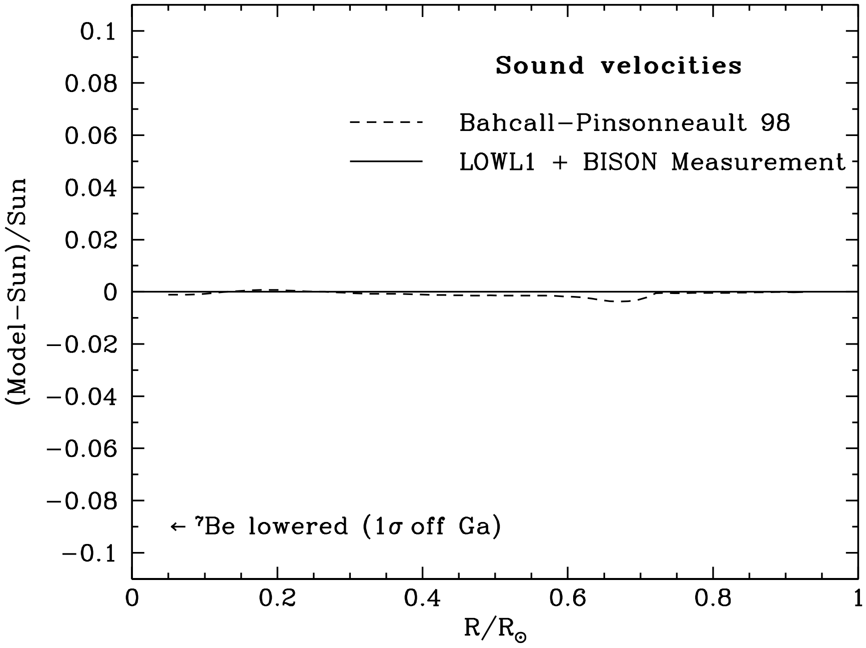

Figure 5: Predicted versus Measured Sound Speeds. This figure shows the excellent agreement between the calculated (solar model BP98, Model) and the measured (Sun) sound speeds, a fractional difference of 0.001 rms for all speeds measured between $0.05R_\odot$ and $0.95R_\odot$. The vertical scale is chosen so as to emphasize that the fractional error is much smaller than generic changes in the model, 0.09, that might significantly affect the solar neutrino predictions.

speeds scale like the square root of the local temperature divided by the mean molecular weight and the ^{7}Be neutrino flux scales approximately as the 10th power of the temperature. Assuming that the temperature changes are dominant, agreement to within 1σ would require fractional changes of order 0.09 in sound speeds, if all model changes were in the temperature. This argument is conservative because it ignores the ^{8}B and CNO neutrinos which contribute to the observed counting rate and which, if included, would require an even larger reduction of the ^{7}Be flux.

I have chosen the vertical scale in Fig. 5 to be appropriate for fractional differences between measured and predicted sound speeds that are of order 0.09 and that might therefore affect solar neutrino calculations. Fig. 5 shows

Table 1: Neutrino Oscillation Solutions.

Solution	Δm^2	$\sin^2 2\theta$
SMA	5×10^{-6} eV^2	5×10^{-3}
LMA	2×10^{-5} eV^2	0.8
LOW	8×10^{-8} eV^2	0.96
VAC	8×10^{-11} eV^2	0.7

that the characteristic agreement between solar model predictions and helioseismological measurements is more than a factor of 100 better than would be expected if there were a solar model explanation of the solar neutrino problems.

7 Solar Neutrino Oscillations

The experimental results from all five of the operating solar neutrino experiments (chlorine, Kamiokande, SAGE, GALLEX, and SuperKamiokande) can be fit well by descriptions involving neutrino oscillations, either vacuum oscillations (as originally suggested by Gribov and Pontecorvo) or resonant matter oscillations [as originally discussed by Mikheyev, Smirnov, and Wolfenstein (MSW)].

Table 1 summarizes the four best-fit solutions that are found in the two-neutrino approximation.

8 Extragalactic Neutrinos

Figure 6 shows the extraordinary sensitivity to neutrino oscillation of experiments like AMANDA, ANTARES, and NESTOR that can detect neutrinos from distant extragalactic sources. I have placed these experiments in Fig. 6 at the position that is appropriate for high-energy (10^{14} eV) neutrinos from gamma-ray bursts (GRBs). Because these sources may lie at modest to large redshifts and because we know the time of the explosion to an accuracy ~ 10 sec (from the gamma rays), GRBs can be used to test special relativity to an accuracy of 1 part in 10^{16} and to test the weak equivalence principle

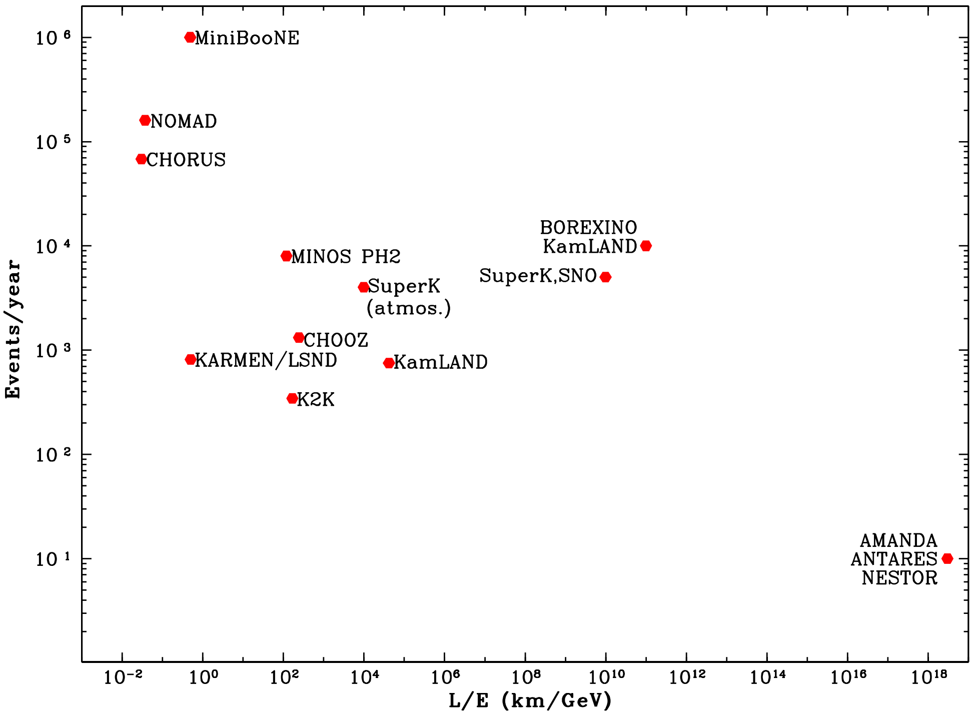

Figure 6: Very longbaseline neutrino oscillation experiments. The figure shows that experiments such as AMANDA, ANTARES, and NESTOR which may detect high-energy neutrinos from distant gamma-ray bursts have extraordinary sensitivity to vacuum neutrino oscillations.

to an accuracy of 1 part in 10^6. GRBs are expected to produce only ν_e and ν_μ. The large area detectors of extragalactic neutrinos are in principle sensitive to vacuum neutrino oscillations with mass differences as small as $\Delta m^2 \geq 10^{-17}$ eV^2 $(\nu_\mu \rightarrow \nu_\tau)$.

The photon phenomenology of gamma-ray bursts is now relatively well understood. Many different types of observations have been carried out and the results are relatively well summarized by the expanding fireball model. Using this model, one can work out the flux of neutrinos from the internal shocks. The observed population of GRBs should give rise to ~ 10 events per km^2 per year from neutrinos with characteristic energies of order 10^{14} eV. The fundamental assumption used in obtaining this number is that GRBs produce the observed flux of high-energy cosmic rays, an assumption for which Eli Waxman has provided a strong plausibility argument.

The search for high-energy neutrinos from GRBs will allow us to test our understanding of the astrophysics of these fascinating objects and, in the same experiment, to investigate neutrino oscillations and relativity with unprecedented precision.

9 Conclusion

I began this talk by comparing where we are today in neutrino astronomy with where we were in 1984, the year of the first Inner Space/Outer Space workshop. I would like to close with some speculations on where we will be in 2014, an appropriate time for the third workshop on Inner Space/Outer Space.

In 2014, we will be very ready to observe a nearby supernova in neutrinos, but we would have to be somewhat lucky to have one go off in our Galaxy by then. I am confident that the parameters which characterize atmospheric neutrino oscillations will be well determined by 2014 and that there will have been successful verifications of the oscillation phenomena with terrestrial long baseline experiments. I believe we will also know by then the basic parameters that give rise to solar neutrino oscillations and will be beginning to use solar neutrinos to study accurately the theory of nuclear burning in the sun, the original goal of solar neutrino astronomy. To be certain that we understand the weak interactions that determine solar neutrino phenomena, we must have direct observations of the fundamental *pp* neutrinos and their energy spectrum. Although *pp* neutrinos constitute more than 90% of the solar neutrino flux according to the standard solar model, their direct detection will be difficult because the maximum energy of *pp* neutrinos is only 0.4 MeV. Finally, I hope and expect that neutrino astronomy will have extended by 2014 to the relatively frequent detection of extragalactic neutrinos from sources like gamma-ray bursts.

Acknowledgments

I am grateful to Josh Frieman, Rocky Kolb, and Mike Turner for giving me the opportunity to participate in a stimulating workshop that was appropriately dedicated to David Schramm. I acknowledge support from NSF grant #PHY95-13835.

References

[1] *Inner Space/Outer Space: The Interface Between Cosmology and Particle Physics*, edited by Edward W. Kolb, Michael S. Turner, David Lindley, Keith Olive and David Seckel (Chicago: University of Chicago Press, 1986).