SUMMARY TALK: INTERNATIONAL SYMPOSIUM ON NEUTRINO ASTROPHYSICS, TAKAYAMA/KAMIOKA (10/’92)

John BAHCALL
Institute for Advanced Study
Princeton, New Jersey 0854
USA

Contents

1. The Conference
2. Solar Neutrinos
   A. Operating Experiments
   B. New Funded Experiments
   C. Are Solar Neutrino Fluxes Time Dependent?
   D. Have \( pp \) Neutrinos Been Detected?
   E. Is Directionality Required for Astronomical Observations?
   F. Is There a Solar Neutrino Problem?
   G. What Have We Learned?
3. Supernova Neutrinos
4. Atmospheric Neutrinos
5. High-Energy Neutrinos
6. Our Field Is Flourishing

1. The Conference

This has been a great conference, packed with important science and arranged with style, tact, thoughtful consideration for the participants, and deep scientific insight. It is one of the best organized conferences I have attended. The character of the organization is typified by the quiet way a young student boarded our bus just before we departed at 7:30 A.M. on our trip to the historic Kamiokande facility. The student asked that all of the speakers for that day raise their hands and then went to each speaker to tactfully inquire if they had remembered to bring their viewgraphs. I am sure I speak for all of us who attended the conference in expressing our gratitude to J. Arafune (Chair of the Organizing Committee), to Y. Totsuka (Co-Chair), and to K. Nakamura (Scientific Secretary), and to their many younger associates. All of these people worked hard and effectively to maximize the scientific benefit and the personal enjoyment for each participant. I found it especially exciting to meet the excellent young Japanese scientists whose names were known to me previously only from their appearance on a long list of Kamiokande authors.

The international and local organizing committees managed to bring together, in addition to the many younger people flushed with the excitement of developing new ideas, the
Four Founding Fathers of Neutrino Astrophysics. It was great to see Davis, Koshiba, Reines, and Zatsepin, together with their (intellectual) sons, Kirsten and Totsuka, struggling with the latest scientific challenges and providing inspiration and insight to all of us. In their epochal experimental researches these individuals have demonstrated originality, perseverance (i.e., stubbornness), and enormous achievement. Their combined presence enhanced the scientific success of the meeting.

In this summary talk, I will discuss four themes of the meeting: solar neutrinos, atmospheric neutrinos, supernova neutrinos, and high energy neutrinos. There were other topics covered beautifully at the meeting, including baryon number violation and grand unification, X-ray astronomy, γ-ray astronomy, gravitational waves, dark matter, and cosmology. I will not cover these non-neutrino talks here in order to keep this summary to a reasonable length. For simplicity, I will not list references for material discussed in the talks, but will instead give the name of the speakers at the conference whose contributions in this book cover the topic under discussion. The statements based on the standard solar model are taken from Bahcall and Pinsonneault (Rev. Mod. Phys., 64, 885, 1992); this paper presents the only published solar eigen-models in which helium diffusion was included in the calculations of the neutrino fluxes. The justification for other statements made without explicit attribution about solar neutrinos or about supernovae can be found in Neutrino Astrophysics, Cambridge University Press (1989).

2. Solar Neutrinos

Solar neutrinos was the most extensively discussed topic at the meeting; it is the most thoroughly developed of the four areas of neutrino research we discussed.

A. Operating Experiments

Table 1 summarizes the results presented at this conference for the four solar neutrino experiments that are currently taking data, the $^{37}$Cl, Kamiokande ($\nu + e^{-}$ scattering), SAGE ($^{71}$Ga), and GALLEX ($^{71}$Ga) experiments. I list in Table 1 the energy threshold, the neutrino sources, measured rate, and calculated rates (Standard Solar Model). The measured rates are all given at this conference by Davis ($^{37}$Cl), Y. Suzuki (Kamiokande), Zatsepin (SAGE), and Kirsten (GALLEX); the rates for the standard solar model are from Bahcall and Pinsonneault. I have listed the average counting rates in Table 1. Since the neutrino fluxes are predicted to be constant to measurable accuracy by the standard solar model, one must use the average fluxes for tests of this model. The last column contains the maximum likelihood estimate for the total number of neutrino events counted to date in each experiment.

I have given in the first column the names of the speakers who described each of these experiments so that you can find the details in the conference proceedings.

Of special note in Table 1 is the large difference, a factor of almost four (many standard deviations), between the calculated and the observed rates for the chlorine experiment and the more moderate discrepancy, a factor of two, for the neutrino-electron scattering experiment. The chlorine experiment is sensitive to neutrinos above 0.8 MeV whereas Kamiokande is only sensitive to higher energy neutrinos (above 7.5 MeV). If new physics is operating, the different energy sensitivities could explain the fact that the chlorine and the Kamiokande experiments differ from the standard model predictions by two and four, respectively.
The two gallium experiments, GALLEX AND SAGE, are in satisfactory agreement with each other, although with their currently large statistical errors it is difficult to say anything very definitive until they have been operating for a longer period. The gallium calibration measurements with intense $^{51}$Cr sources will provide very important tests of our understanding of how these experiments work; the calibration measurements will begin in about a year for both experiments. Ultimately, when the two independent experiments have been operating for several years—and when both have been calibrated with external radioactive sources—we will have have a very reliable number for the solar neutrino capture rate on gallium.

**B. New Funded Experiments**

Table 2 describes the four new solar neutrino experiments that have been funded for development. Each of the modes of each of the experiments listed in Table 2 is expected to yield more than 3,000 neutrino events per year (except for the $\nu - e$ scattering mode of SNO). In one year, each experiment will record three or more times the total number of neutrino events that have been counted to date in all solar neutrino experiments since the chlorine experiment began operating a quarter of a century ago. With this much greater statistical accuracy, we can expect our subject to become much more precise.

The experiments are listed in order of their expected completion dates, SNO (1995), Super Kamiokande (1996), BOREXINO (~1996), and ICARUS (1998). Table 2 lists the neutrino threshold energy for each reaction mode and the individual reactions that will be observed.

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Table 1. Solar Neutrino Experiments.

| Target       | Energy Source(s) | Measured  | SSM† | Neutrino Counts |
|--------------|------------------|-----------|------|-----------------|
| $^{37}$Cl (Davis) | $\geq 0.8$ All but $pp$ | $2.23 \pm 0.23$ | $8.0 \pm 1.0$ | 750 |
| $\nu + e$ (Suzuki) | $\geq 7.5$ $^8$B | $0.49 \pm 0.04 \pm 0.06$ | 1.0 | 380 |
|              | $\geq 18$ $hep$ | $< 49$    | 1.0  |
|              | 13 $\nu_e$     | $< 0.06 \phi_{SSM}(^8$B) | 0.0 |
| $^{71}$Ga (SAGE, Zatsepin) | $\geq 0.2$ All | $58^{+17}_{-24} \pm 14$ | $132^{+7}_{-6}$ | 25 |
| $^{71}$Ga (GALLEX, Kirsten) | $\geq 0.2$ All | $83^{+20}_{-19} \pm 8$ | $132^{+7}_{-6}$ | 75 |

† Average over time. Statistical errors quoted are effective 1σ values; statistical errors precede systematic errors.
Table 2. New Solar Neutrino Observatories.

Typical Event Rates $\gtrsim 3 \times 10^3$ yr$^{-1}$

| Observatory         | $E_{Th}(\nu)$ (MeV) | Reaction(s)                                                                 |
|---------------------|----------------------|-----------------------------------------------------------------------------|
| SNO (Ewan)          | 6.4                  | $\nu_e + ^2\text{H} \rightarrow p + p + e^-$                               |
|                     | 2.2                  | $\nu + ^2\text{H} \rightarrow n + p + \nu$                               |
|                     | 5                    | $\nu + e^- \rightarrow \nu + e^-$                                         |
| Super-Kamiokande (Takita) | 5          | $\nu + e^- \rightarrow \nu + e^-$                                         |
| BOREXINO (Raghavan) | 0.25                 | $\nu(^7\text{Be}) + e^- \rightarrow \nu(^7\text{Be}) + e^-$                |
| ICARUS (Revol)      | $\sim 10$           | $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{Kr}^*$               |
|                     | 5                    | $\nu + e^- \rightarrow \nu + e^-$                                         |

The SNO experiment has, as George Ewan told us, two unique capabilities: SNO will measure precisely the energy spectrum of electron-flavor neutrinos above about 5 MeV in the charged current reaction (neutrino absorption by deuterium) and will measure the total neutrino flux independent of flavor in the neutral current reaction (neutrino disintegration of deuterium). The comparison of the fluxes measured via neutrino absorption on deuterium and by neutrino disintegration of deuterium will test the equality of the charged and the neutral currents. If the total neutrino flux is not equal to the electron neutrino flux, then we will have direct evidence for neutrino flavor changing. (The two measured fluxes would also be equal if electron neutrinos change only into sterile neutrinos.)

I am delighted that the SNO collaboration is giving first priority to determining the shape of the $\nu_e$ energy spectrum; the shape of this function is independent of solar astronomy (to an accuracy of one part in $10^5$, Phys. Rev. D, 44, 1644, 1991). A measurement of the neutrino energy spectrum could establish that physics beyond the standard electroweak model is required, independent of any consideration of solar physics. The charged and neutral currents must be equal unless some neutrinos change their flavor after they are created in the solar core. Unfortunately, no energy information will be available for the neutral current detection. Also, the neutral and charged-current fluxes would be equal even if some of the original electron-type neutrinos changed into sterile neutrinos.

I was excited to hear from Revol that the ICARUS collaboration has successfully completed testing a 3-ton prototype. The welcome news about ICARUS indicates that this very important experiment, which will have a unique “smoking-gun” mode of detection of solar neutrinos (gamma rays accompanying neutrino-produced electrons), will proceed as planned.

Note that some redundancy will be available if all four experiments operate as planned. The ICARUS experiment will provide a precise measurement of the $\nu_e$ energy spectrum above about 10 MeV, which can be compared with the energy spectrum measured by SNO. Three experiments (Super Kamiokande, SNO, and ICARUS) will measure for $^8\text{B}$ neutrinos the $\nu_e - e^-$ scattering rate and the recoil electron energy spectrum; the electron recoil spectrum reflects the incoming neutrino energy spectrum. Takita showed us, for example, how well Super Kamiokande can distinguish—by measuring the electron recoil energy spectrum—between the small difference in the electron recoil spectrum for the two MSW solutions that are allowed...
by the existing experiments.

The BOREXINO experiment is absolutely essential. It is the only experiment planned for this decade that will measure the energy of individual events with energies less than 5 MeV. This information is necessary in order to determine the neutrino survival probability at low energies. The BOREXINO experiment also has another highly desirable feature; it measures the $\nu_e$ flux at a specific energy. One does not have to average the theoretical predictions for BOREXINO over energy (and therefore lose uniqueness) as is the case for electron scattering by a continuum neutrino energy source.

The most urgent need in this field is for other low-energy neutrino detectors. No practical solution appears in sight for the fundamental problem of detecting the basic $pp$-neutrinos and only one funded experiment will observe the individual $^7$Be neutrino reactions. Kopylov described a possible $^7$Li radiochemical experiment, but a method still must be developed for counting the $^7$Be atoms that are produced.

Two $\nu_\mu - \nu_\tau$ oscillation experiments at CERN, called CHORUS and NOMAD, will begin operating soon. Although they are vacuum oscillation experiments, CHORUS and NOMAD have the sensitivity in mass to test some of the MSW solutions of the solar neutrino problem that were discussed at this conference. There were no talks on these important experiments, but I think I remember reading that they are expected to be sensitive to mass differences for $\nu_\mu - \nu_\tau$ of the general order of $\gtrsim 10$ eV$^2$ with $\sin^2 2\theta \gtrsim 10^{-3.5}$ or so. A similar experiment, NUMI, is planned at FNAL. These laboratory experiments are important tests of standard model physics and may, in addition, be crucially related to the astronomical interpretation of the observed solar neutrino fluxes.

C. Are Solar Neutrino Fluxes Time Dependent?

Do the observed event rates vary with time? They are not expected to do so since the characteristic cooling time in the solar core is of order $10^6$ years and since the important nuclear reaction rates have lifetimes between $10^4$ and $10^{10}$ years. The only way that has been found to account for the suggested $\sim 11$ year cyclic dependence is to invoke new physics incompatible with the standard electroweak model, a large neutrino magnetic moment (discussed at this conference by Lim).

The Kamiokande data are not correlated with sunspot intensity, as was shown clearly by Y. Suzuki in his lecture. Davis pointed out that the chlorine data also show no indication of a correlation with sunspots during the period in which the Kamiokande experiment was operating. What’s more, the chlorine data do not indicate any correlation for the first seven year period of data taken between 1970 and 1977. The data do show an apparent dependence on sunspot cycle for the two cycles that are sandwiched between apparently constant rates. My view is that this seeming correlation is most likely a fluke occurrence in noisy data, but it is very important to continue the chlorine measurements to obtain information about any long-term trends or time-dependences in the data. This is especially true since, as Kopylov told us, the chlorine experiment does not appear likely to be repeated.

Fortunately, the average rate observed in the chlorine experiment is robust. The average rate observed in the initial (non-varying) period from 1970–1976 is $(2.0 \pm 0.35)$ SNU; the average rate observed (when variations have been suggested) from 1977–1990 is $(2.1 \pm 0.2)$ SNU and, as Davis told us in his talk, the average of all the data is 2.23 SNU. I conclude that the average rate of neutrino captures observed over a long period (a number of years) is well determined and it is this quantity that we need to test the standard model.

D. Have $pp$ Neutrinos Been Detected?

What do the gallium experiments tell us about the fundamental $pp$ neutrinos? Radiochemical experiments have only an energy threshold but no energy resolution. Therefore,
all that we know is that, e.g., for the GALLEX experiment the observed event rate is approximately \(83 \times 10^{-36}\) captures per target atom per sec, i.e., 83 SNU. To go further, we must compare the observed event rate with the expected event rates from different sources as predicted by the standard solar model. The total predicted rate from all solar sources is 132 SNU and the rate predicted from \(pp\) (and \(pep\)) neutrinos alone is 74 SNU. The similarity between the \(pp\) rate in the standard solar model, 74 SNU, and the observed GALLEX rate, 83 SNU, has suggested to some that GALLEX has “definitely” observed the \(pp\) neutrinos. But, the rate expected in the standard solar model from all neutrinos except \(pp\) neutrinos is also reasonably close (with the current large statistical errors) to the observed rate. The “all but \(pp\) rate” is equal to: 36 (from \(^7\)Be) + 8 (from CNO) + 7 (from \(^8\)B; rate halved because of Kamiokande result). The total from “all but \(pp\)” is therefore 51 SNU.

Table 3 compares the observed versus expected (standard solar model) rates for the \(pp\) neutrinos, the “all but \(pp\) neutrinos,” and the total standard model fluxes. Both the GALLEX and the SAGE experimental rates are within 1\(\sigma\) of the value expected for \(pp\) neutrinos only, but neither experiment is as much as 2\(\sigma\) away from the value expected for “all but \(pp\).” Both experiments are more than 2\(\sigma\) away from the standard solar model value (SAGE is more than 4\(\sigma\) away). I conclude that there is some experimental indication that \(pp\) neutrinos are being observed in the gallium experiments, but (and this is usually not emphasized) the evidence for a discrepancy with the standard solar model is stronger than the evidence that \(pp\) neutrinos are being detected.

| Exp. | Obs.–\(pp\) | Obs.–(all but \(pp\)) | Obs.–SSM |
|------|-------------|------------------------|---------|
| GALLEX | 9           | 32                     | 49      |
| 83 SNU | (0.5\(\sigma\)) | (1.7\(\sigma\))     | (2.5\(\sigma\)) |
| SAGE   | 16          | 7                      | 74      |
| 58 SNU | (0.9\(\sigma\)) | (0.4\(\sigma\))     | (4.3\(\sigma\)) |

† Only statistical errors included in \(\sigma\).

What do we need to do to sharpen the test for the presence of \(pp\) neutrinos? The statistical errors must be reduced in the gallium experiments. But, it is also essential to determine if the gallium experiments are really observing 36 SNU from the \(^7\)Be neutrinos, as suggested by the standard solar model. Fortunately, as Raghavan told us, BOREXINO should give us a good value for the \(^7\)Be neutrino flux.

E. Is Directionality Required for Astronomical Observations?

Suzuki showed a dramatic figure demonstrating that the neutrinos observed by Kamiokande come from the direction of the sun. This result is of great importance scientifically and I personally was thrilled to see this clear demonstration of solar origin (for amusement see the first theoretical discussion of this effect in Phys. Rev. B, 135, 137, 1964).

I do not agree with the statement made by Koshiba that a solar neutrino experiment must have directionality in order to be considered astronomy. The sun is the overwhelming source of locally-observed neutrinos for the same reason that the sky is bright in the day and is dark at night. A numerical calculation summarized in Section 6.5 of Neutrino Astrophysics gives a ratio of more than \(10^9\) for solar to non-solar neutrinos in the Kamiokande energy range. Moreover, the solar neutrino flux is certainly less than or equal to the total neutrino flux observed in the (non-directional) chlorine and gallium experiments. Since the total observed flux is less than the calculated flux from solar models, the chlorine and gallium experiments
provide important information about the sun that does not depend upon knowing that the sky is dark at night. Of course, the most straightforward astronomical inferences assume—for directional as well as non-directional experiments—that nothing happens to the neutrinos after they are created.

The last two Decade Surveys for Astronomy (conducted by the National Academy of Sciences) in the United States have pointed to the chlorine experiment as a major contribution to astronomical knowledge and have strongly advocated the gallium experiments. Wearing my hat as president emeritus of the American Astronomical Society, I can say that we astronomers are proud to claim the chlorine, gallium and the (future) BOREXINO experiments as important astronomical observatories.

F. Is There a Solar Neutrino Problem?

Finally, we need to consider the fundamental question of our subject: Is there a solar neutrino problem? The answer is “yes,” because the chlorine and Kamiokande experiments are inconsistent with the most accurately calculated solar models. In the 30 years that I have been calculating solar neutrino fluxes, no one has produced a solar model with conventional physics that has neutrino fluxes in agreement with the chlorine experiment. The $^8$B neutrino flux observed by Kamiokande exceeds by $2\sigma$—if nothing changes the neutrino energy spectrum—the equivalent event rate in the chlorine experiment. Moreover, the two gallium experiments are more than $2\sigma$ away from the standard model predictions.

The most decisive way of exhibiting the discrepancy between the standard model calculations and the observations is to show the results of the Monte Carlo calculation for 1000 solar models when the $^8$ fluxes for each model are replaced with the experimental value obtained by the Kamiokande experiment. This histogram is shown in Figure 1, taken from a recent paper by Hans Bethe and myself. Even if the uncertainties associated with the calculation of the $^8$ flux are artificially removed by adopting the Kamiokande value for this quantity, the calculated event rate is inconsistent with the observed event rate in the chlorine experiment. Not one model in 1000, even with the measured Kamiokande flux, is within the $3\sigma$ error limit of the chlorine experiment. In my view, this is the core of the “solar neutrino problem.”

It is of course possible that one or more of the existing experiments is incorrect. I do not think this is likely, but the history of science has taught us that important experiments must be confirmed by different techniques in order to derive secure conclusions. Any new experiment that can provide unambiguous information about solar neutrino fluxes is highly desirable.

G. What Have We Learned?

The Kamiokande and chlorine experiments show that—although there is a discrepancy with the standard solar model—the $^8$B neutrino flux at the earth is $\sim 3 \times 10^6$ cm$^{-2}$s$^{-1}$. This point was stressed by Ray Davis.

From an astronomical point of view, this is a great achievement. The fact that the standard solar model predicts a $^8$B neutrino flux within a factor of two of the measured value is a unique and sensitive confirmation of the basic ideas of stellar evolution and of nuclear energy generation in stars.

If all four of the operating experiments are correct, then the chlorine and Kamiokande results show that, in addition, new physics is required (see Figure 1). The gallium experiments then fix (approximately) the MSW parameters that can describe all the observational results. As Smirnov and Pakvasa told us, the standard MSW solutions are then: $\delta m^2 \sim 10^{-6}$ eV$^2$($\sin^2 2\Theta \ll 1$) or $\delta m^2 \sim 10^{-5}$ eV$^2$ to $10^{-4}$ eV$^2$($\sin^2 2\Theta \sim 0.5$). There is an additional allowed region with $\delta m^2 \sim 10^{-6}$ eV$^2$ to $10^{-8}$ eV$^2$, also at large mixing angles.
The new experiments listed in Table 2 will either confirm and extend these conclusions or reveal that there is some (currently unknown) fundamental error in one of the experiments or in the solar model calculations.

3. Supernova Neutrinos

We heard clear descriptions of the theoretical expectations for supernova neutrinos and, with great honesty, the difficulties that must be overcome to make accurate calculations. The talks by Sato, Janka, H. Suzuki, Burrows, and Nomoto convinced me that the problems are fascinating as well as formidable. It is clear that the theory is on the right track, since the pre-existing predictions gave for supernova 1987A the total neutrino energy correct to better than an order of magnitude, and also gave good estimates for the average temperature of the electron anti-neutrinos and for the duration of the burst. These later two calculations are particularly impressive since they depend upon the result of neutrino trapping as the neutrinos diffuse out of the stellar core, which converts a population of several hundred MeV neutrinos to a swarm of neutrinos with characteristic energies of order 10 MeV or less.

Each time that I get a little depressed by the seemingly endless detail and the great precision that are required to compute an accurate solar model, I think of the much greater difficulties that my friends working in the field of supernova neutrinos must overcome. As a measure of the relative difficulty of the solar and supernova problems, and as an indication of how much smarter the supernova theorists have to be than I am, here are some relevant dimensionless ratios:

$$\frac{\rho(\text{neutron star})}{\rho(\odot)} \sim 10^{+12}, \quad \frac{\tau(\odot)}{\tau(\text{supernova})} > 10^{18}, \quad \frac{E(\text{supernova})}{E(\text{solar flare})} > 10^{20}. $$

Here $\rho$ is the local density, $\tau$ is the lifetime (of the main sequence sun or the supernova collapse), and $E$ is the total energy (of the supernova explosion or of a large solar flare).

We heard descriptions of several existing and potential supernova detectors at this conference, including Kamiokande (Y. Suzuki), MACRO (Spinetti), Baksan (Kopylov), SNO (Ewan), Super Kamiokande (Takita), ICARUS (Revol), Soudan 2, and LVD. Once all of these detectors are operating, we will be well equipped to study Galactic supernovae. In fact, the Kamiokande, MACRO, Baksan, and LVD detectors are already obtaining valuable limits on the possible occurrence of supernovae anywhere in the Galaxy (including regions that are hidden by dust from visible observations).

Krauss presented some results of a menu-driven Monte Carlo simulation program that illustrate what can be learned about supernovae and about neutrino physics by observing an explosion with Kamiokande or Super Kamiokande. The results were very interesting and in some cases unexpected. The difficulty of detecting the initial neutronization burst, for example, was surprising but in retrospect understandable.

Koshiba proposed in his talk that a very large detector be built to observe extragalactic supernovae and Cline proposed a network of supernovae detectors. Both of these proposals are aimed at achievable and fundamental astronomy and physics goals. Either of the proposals is feasible, in my opinion, provided a group of people dedicate themselves to making the dreams a reality over the approximately one decade necessary to persuade the community, to obtain funding, and to construct the detectors.

Tammann described a determination of the rate for Galactic supernovae of one per $33^{+12}_{-7}$ years, using both extragalactic and Galactic supernovae. I found Tammann’s description of his analysis fascinating, including the difficult factors that must be understood such as the effects of dust hiding Galactic supernovae, the small number (5) of historic Galactic supernova, and the effects of galactic type, inclination, and $H_0$ in the determination of the rates of
extragalactic supernovae. One of the crucial elements in Tammann’s determination is the calibration of the efficiency of the amateur astronomers in detecting supernovae in extragalactic nebulae. I could not erase from my mind the irreverent image of Tammann on a dark night creeping up to Reverend Evans as he concentrated on the heavens and measuring the dilation of the Reverend’s pupils with a micrometer.

A number of different methods have been applied to the calculation of the Galactic supernova rate and these yield expected rates ranging from the lowest calculated value of 11 years (from the computed death rate of massive stars) to more than 60 years (from pulsar statistics). As Tammann told me privately, “the determination of the Galactic supernovae rate is harder than measuring $H_0$,” for which he is also famous. The systematic errors in the subject should be reduced when the results of the Berkeley automatic supernova detection survey and similar surveys have accumulated sufficient observing time.

4. Atmospheric Neutrinos

The ratio of muon to electron neutrinos from atmospheric cascades was reported to be lower than expected in both the Kamiokande (Kajita) and the IMB (Dye) experiments. In both cases, the observed ratio, $R$, of $\nu_\mu$ to $\nu_e$ events is less than the ratio expected from Monte Carlo simulations. No matter how the experimental cuts were made, the ratio of ratios was always found to be approximately in the range:

$$\frac{R \left( \frac{\mu}{e} \right)_{\text{Obs.}}}{R \left( \frac{\mu}{e} \right)_{\text{MonteCarlo}}} = (0.60 \text{ to } 0.65) \pm 0.05.$$  

This result is highly significant statistically, but the systematic errors require further investigation.

Gaisser and Honda gave explicit discussions of the ingredients that went into the predictions of the $\nu_\mu$ to $\nu_e$ ratio and stressed the various uncertainties in the input data of the theoretical calculations. The robustness of the theoretical predictions is remarkable. Gaisser stressed that this is partly because the uncertainties in the primary cosmic ray beam that produce all of the secondaries affect both types of neutrinos in the same way. Also, the uncertainties in the data on pion and kaon production as the cosmic rays cascade through the atmosphere affect both types of neutrinos similarly.

I was puzzled by the fact that many of the senior experimentalists with whom I discussed the problem—some coauthors on the papers being presented—felt that the discrepancy might “go away,” but could not highlight specific weaknesses in the arguments. Perhaps they were influenced by the 15% change in the calculated ratio due to muon polarization (pointed out by Volkova) and they are waiting for another couple such revisions.

The measurements of the $\nu_\mu/\nu_e$ ratio could have wide-ranging consequences for physics, including the possibility of a $\nu_\mu$ to $\nu_e$ mixing with a mass difference $\delta m^2 \gtrsim 10^{-2}$ eV$^2$. However, I think we need to understand in more detail all aspects of the problem. Most importantly, we need to identify clearly and scrutinize most carefully those aspects of the calculation that can affect the predicted $\nu_\mu/\nu_e$ ratio such as: the experimental discrimination between $\nu_\mu$ and $\nu_e$ events, the guts of the Monte Carlo simulations, the implications of the discrepancies between the calculated and observed absolute rates, the percentage of produced muons that decay in transit; the composition of the primary cosmic rays (which affects the ratio of $\nu_e$ to $\bar{\nu_e}$), and the relevant cross sections for quasi-elastic neutrino interactions in nuclei. Precise measurements of the primary flux and of the muon flux at high altitudes would be helpful in resolving some of the ambiguities in the neutrino flux calculations, as stressed by Gaisser.

In the early days of the solar neutrino problem, there were several intense meetings with small groups in which Ray Davis and I described our respective parts of the problem and experts in chemistry, in nuclear physics, in high energy physics, and in astronomy probed for the weak spots in the arguments. These meetings were informal study sessions, much like
oral Ph.D. examinations, where questions could be examined and discussed in depth. They had the opposite flavor from the currently-popular large conferences. A number of tests and checks, both experimental and theoretical, were suggested in these small meetings that led all of us to understand the problem better and to ultimately have confidence in what we are doing. Perhaps something similar should be tried with the atmospheric $\nu_\mu$ to $\nu_e$ ratio. A group of people interested in the details and expert in different aspects of the subject could get together with the experimentalists and theorists involved in the problem for some detailed but essentially private discussions of what is going on. My expectation is that this would lead to a better understanding and ultimately a greater confidence in the final results.

5. High-Energy Neutrinos

The possibility of observing high-energy neutrinos ($\gtrsim 100$ GeV) with AMANDA (Halzen) or DUMAND (Learned) is thrilling. There are fabulous possibilities for detecting different kinds of sources, including the debris from high-energy cosmic ray interactions in the interstellar medium, dark matter annihilation in the sun, and shock waves in active galactic nuclei. In all cases, the basic process is protons crashing into something and thereby producing pions and muons that decay into neutrinos (and other less penetrating products).

Halzen pointed out that if the high-energy gamma rays from Mrk 421 are produced by proton collisions instead of by the inverse Compton effect then AMANDA should see many events per year from this source. (An angular resolution of order one degree is expected.) In such a case, there could well be many more high-energy neutrino sources than high-energy gamma ray sources since intergalactic starlight probably creates an appreciable opacity to high-energy gamma rays but not to high-energy neutrinos.

AMANDA and DUMAND will explore a frontier of the Universe. It is hard to know what they will find, but the results might well dominate meetings on Neutrino Astrophysics in the second half of this decade.

6. Our Field Is Flourishing

Solar neutrino astronomy has become a mature field with four operating experiments and four more planned experiments that will increase the data rate by almost two orders of magnitude. Until the new experiments are operating, we will have to make use of solar model calculations of the expected fluxes in order to interpret the results. Doing this, we mix together possible new physics with possible new astronomy. One of the most wonderful aspects of the new experiments is that they will make possible precision tests— independent of solar considerations—of the shape of the $^8$B energy spectrum and of the ratio of charged to neutral current fluxes. In addition, we should be able to see for the first time individual events from the low-energy $^7$Be neutrino line. The results of the new experiments will be rich in the information they provide about physics and about astronomy. At present, we can say that all four of the existing solar neutrino experiments disagree with the standard solar model and that the chlorine and Kamiokande experiments cannot both be correct if the $^8$B solar neutrino spectrum is not changed by new physics. I believe that it is likely that new physics is being revealed by the existing solar neutrino experiments, but history teaches us that we must be cautious about reaching conclusions until the results are confirmed by different experiments. It is possible that the new CERN and FNAL $\nu_\mu - \nu_\tau$ oscillation experiments will show that neutrino oscillations—the most attractive theoretical explanation of the solar neutrino problem—do occur in nature.

Several neutrino detectors are currently operating that could provide detailed information about Galactic supernova explosions and perhaps even reveal a cosmologically interesting neutrino mass. As we gain more experience with the existing and under-construction new detectors, I hope we will be encouraged to build even larger detectors capable of reaching to
distances sufficient to detect every year neutrinos from supernova explosions.

We can look forward to a more intense scrutiny of the $\nu_\mu$ to $\nu_e$ ratio in the atmospheric cosmic rays. New experiments (such as MACRO), and more detailed examination of the already-available results, should clarify this puzzle and perhaps present us with another well-defined problem that could conceivably point to physics beyond the standard electroweak model.

Finally, there is the awesome possibility that high-energy neutrinos will be observed in AMANDA, DUMAND, and other large-area detectors, extending the frontier of astronomy to high-energy neutrinos and opening a new window to the Universe.