Neutrino Astrophysics

A.B. Balantekin*
Department of Physics, University of Wisconsin, 1150 University Ave, Madison, WI 53706

S. Barwick†
Department of Physics and Astronomy, 4129 PS2 4575, Irvine CA 92697-4575

J. Engel‡
Department of Physics and Astronomy, CB3255,
University of North Carolina, Chapel Hill, NC 27599-3255

G.M. Fuller§
Department of Physics, University of California, San Diego, La Jolla, CA 92093-0319
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We review the recent accomplishments, key scientific questions, and prospects for the future of neutrino astrophysics. These issues were discussed in section P4.7 (neutrino astrophysics) at the Snowmass 2001 workshop.

I. INTRODUCTION

Neutrinos from outside the earth have recently provided some of the most exciting discoveries in particle physics. Experiments with atmospheric and solar neutrinos indicate flavor oscillations and non-zero neutrino masses. The next genertaion of such experiments will pin down the neutrino mixing parameters and masses, at the same time as they look for proton instability. Other detectors, looking at higher-energy neutrinos can tell us about the possibilities of neutralino dark matter, sterile-neutrino dark matter, the fundamental physics behind cosmic rays that seem to be too high in energy to reach the earth, and the possible violation of Lorentz and other fundamental symmetries.

These same experiments provide information about the physics of the sun, supernova explosions, and cosmic-ray and gamma-ray sources. And theoretical work on the effects of neutrino mixing and magnetic moments in leptogenesis, supernova explosions, nucleosynthesis, etc. can teach us about neutrino properites, astrophysics, and cosmology all at the same time.

The recent history and potential for discovery of experiments (and theory) in this field argue that they should be encouranged and supported in the next 10 to 15 years. Below we review some of the outstanding discoveries and discuss future prospects in the field.

II. ATMOSPHERIC NEUTRINOS

Just a few years ago, the study of neutrinos from the atmosphere furnished the first solid evidence for neutrino oscillations. The most compelling result, the zenith angle dependence of the mu-neutrino flux, made the reality of oscillations a concensus opinion. In the simplest interpretation, the experiments point to an oscillation between ν_μ and ν_τ with a mixing angle of $\sin^2(2\theta) \gtrsim .9$ and a Δm^2 of $1 - 5 \times 10^{-3}$ eV^2.

Atmospheric neutrino experiments are powerful because the neutrinos that are detected span a large range of baselines and energies. The experiments can thus probe L/E ratios, which in part determine the oscillation probability, over a much larger range than accererators can. Furthermore, the fluxes would be nearly isotropic in the absence of oscillations, so that many uncertainties cancel when measuring up/down asymmetries. These conditions are ideal for disappearance experiments, and atmospheric neutrions have opened a door on new physics.

*baha@nucth.physics.wisc.edu
†barwick@cosmic.ps.uci.edu
‡engelj@physics.unc.edu
§gfuller@ucsd.edu

Of course we'd like to know much more about neutrino properties. The chief scientific questions addressable by atmospheric-neutrino physics are these: What are the precise masses of the three neutrinos we know exist, and what are their mixings? Are there sterile neutrinos, and how do they mix with the active ones? The answers, besides increasing our knowledge of basic neutrino properties, will help us understand both flavor mixing and the source of mass. In the next few years, experiments with reactor-, solar-, and accelerator-neutrinos will answer the questions in part, but a new generation of atmospheric-neutrino experiments, which will detect neutrinos with much higher statistics and/or larger energy acceptance than Super Kamiokande, is still important. And not just for the increased precision (less than 10%) with which it will determine the atmospheric Δ_m^2.

One question that will still be unaddressed in 5 or 10 years is whether some neutrinos are decaying rather than oscillating; neutrinos in the energy range to which Super Kamiokande is sensitive do not undergo a full oscillation cycle and their disappearance can be explained as exponential decay. New atmospheric-neutrino detectors such as UNO or MONOLITH, by looking at a large range of energies, will be able to distinguish the two possiblities. Equally important, especially if the MiniBOONE experiment confirms the observation of neutrino oscillations by by LSND, is the the ability to untangle oscillations of ν_μ's into ν_τ's from those into sterile neutrinos. Although one or more long-baseline experiments will address this issue by looking for ν_τ appearance, they will have lower statistics and will not be sensitive to a subdominant oscillation into sterile neutrinos. Both MONOLOITH and UNO will be able to meausure ν_τ appearance with high statistics, and MONOLITH at least will be able to distinguish μ^- particles from μ^+'s. These two kinds of measurments should allow conclusions about the numbers of sterile or electron neutrinos produced through oscillations. The ability to measure the charge of muons is important because oscillations of ν_μ's into ν_τ's or ν_s's can be affected by MSW oscillations in the earth, which act differently on neutrinos and antineutrinos. The result would be an unexpected assymmetry in the numbers of positively and negatively charged muons in the detector. It might even be possible to deduce the sign of the atmospheric Δ_m from these experiments, telling us which is the lighter neutrino, as well as measuring its square to much better precision.

Detectors for atmospheric neutrinos can also serve as excellent targets in long-basleine oscillation experiments, perhaps allowing a meaurement of the mixing angle for $\nu_e \to \nu_\tau$ oscillations (down to $\theta_{13} = 10^{-3}$ at UNO) and of CP violation in the neutrino mixing matrix. They will also extend current sensitivity to proton decay, by up to an order of magnitude, examine solar- and supernova-neutrinos, and help calibrate high-energy neutrino experiments. The wealth of information these detectors will supply make them important players in the future of particle physcics.

III. SOLAR NEUTRINOS

Detecting neutrinos from the sun is a valuable to see the sun's interior as well as to learn about the properties of neutrinos. Up until a few years ago, the flux of solar neutrinos was measured by a number of experiments, but the results were been inconsistent and perplexing. The pioneering experiment was Ray Davis's 600 ton chlorine tank (actually dry cleaning fluid) in the Homestake mine, South Dakota. His radio-chemistry assay, begun in 1967, found evidence for only one third of the expected number of neutrino events. Two gallium detectors (SAGE and GALLEX), which have lower energy thresholds, found about 60-70Cherenkov experiment at Kamioka, Japan, upgraded to detect solar neutrinos in 1986, measured one half of the expected events for the part of the neutrino spectrum for which they are sensitive.

The situation changed rather dramatically earlier this year. This year Sudbury Neutrino Observatory (SNO) collaboration, by combining the charged-current breakup of the deuteron with elastic scattering on electrons (measured by the SuperKamiokande detectors and also by SNO), provided the first measurement of the electron neutrino component of the solar neutrino flux from ^{8}B. They found that the solar neutrino flux is composed of roughly one-third electron neutrinos and two-thirds other active flavors. By measuring the total solar neutrino flux they also confirmed the prediction of the Standard Solar Model.

It is important to put the existing experiments and results in perspective: Super-K produced results on the ^{8}B neutrino spectrum of unprecedented accuracy. GALLEX and SAGE have been tested with ^{51}Cr neutrino sources, verifying the nuclear cross sections and the efficiency of the chemistry. SNO succeeded in measuring the total ^{8}B solar neutrino flux. Currently both the increasing precision of helioseismology and the development of solar-model-independent neutrino analyses of the data appear to rule out any possibility of non-standard solar models.

What we can infer from the combined SuperK and SNO measurements is somewhat surprising: It looks like neutrino mixing angles are rather large, unlike the mixing between quarks. In addition these experiments provide rather strong constraints for the mixing between first and second generations as well as the mixing between second and third generations. At this time the amount of mixing between the first and third generations (i.e.

the test of unitarity of the neutrino mixing matrix) and the possible existence of sterile neutrinos that may mix with the active flavors remain as open questions.

In the near future solar neutrino experiments may be able to probe the coupling between first and third generations by measuring low-energy (pp) solar neutrinos in real time. The proposed National Underground Science Laboratory in the United States would provide unique opportinities in this regard as it may provide a location for large neutrino detectors in a very-low background environment.

IV. NEUTRINOS FROM SUPERNOVAE AND IN THE EARLY UNIVERSE

The supernova mechanism involves an extraordinary range of physics ranging from nuclear physics to astrophysics. To understand the initial conditions for the explosion, the massive progenitor star must be evolved through its various burning stages to formation of the inert iron core. This problem couples laboratory nuclear astrophysics – including open problems like the ^{12}C + α S-factor – with stellar evolution, and is very much an extension of the program that began with the solar neutrino problem. The description of the core bounce requires us to predict the behavior of bulk nuclear matter at densities and temperatures not otherwise accessible. New phenomena — mixed or quark-matter phases, color superconductivity, kaon condensation — could affect the equation of state. Both the early deleptonization of the star and the subsequent cooling require a detailed treatment of neutrino transport through the nuclear medium, and an understanding of the various processes that determine the opacity. Shock wave propagation through nuclear matter must be understood. The nucleosynthesis depends on relationships between the explosion dynamics, the neutrino physics, and laboratory astrophysics. The explosion determines the timescale for the nucleosynthesis. Neutrino reactions control the isospin of the nuclear matter. Laboratory astrophysics must determine the masses and the β decay lifetimes important to the r-process and other explosive nucleosynthesis.

The better the mechanism is understood, the more accurate the information we can derive from supernova neutrinos, which provide unique opportunities to learn about neutrino properties. As the neutrinosphere resides at a density $\sim 10^{12}$ g/cm^3, supernovae allow us to extend our tests of matter effects on oscillations by 10 orders of magnitude. Thus MSW effects, even for very small mixing angles of 10^{-5}, can distort the neutrino spectra. The entire range of cosmologically interesting masses can be probed in this way. In particular, supernovae may provide our best laboratory for investigating $\nu_e - \nu_\tau$ oscillations. Detection of the neutrino signature of a Galactic stellar collapse event in terrestrial detectors like SuperK, SNO, and the proposed OMNIS could provide us with key insights into neutrino mass/mixing schemes. Kinematic tests of neutrino mass, for example, can be made by studying arrival times on earth as a function of flavor or energy; in this way it may be possible to greatly reduce mass limits for the ν_τ and ν_μ. The energy spectra of the arriving neutrinos will also provide important information about mixing and masses.

In another vein, there is an experimental neutrino physics revolution underway and, concurrently, an ongoing explosion of capabilities in observational astronomy, from the advent of Keck-class telescopes to space-based x-ray and optical and Cosmic Microwave Background (CMB) observatories. These trends could be synergistic, especially as regards the role of neutrinos in nucleosynthesis and cosmology. For example, Keck-class telescopes recently have provided detailed spectra of Ultra Metal Poor halo stars which reveal puzzling systematics of r-process nuclide abundances. Since many models of r-process nucleosynthesis are sited in environments whose thermodynamic and hydrodynamic histories are dominated by neutrino interactions with nucleons, nuclei, and other leptons, it is natural to ask what effect matter-enhanced neutrino flavor transformation in various mass/mixing schemes would have on nucleosynthesis yields and abundance patterns. We do not as yet know the answer to this question with any degree of certainty.

Likewise, Keck-class telescopes have completely changed the way we view Big Bang Nucleosynthesis (BBN). Observations of isotope-shifted deuterium Lyman series absorption lines along the lines of sight to high redshift QSO's, coupled with the simple nuclear physics of the deuteron, have provided us with an accurate measure of the baryon number of the universe. This number is consistent with measures of the same quantity obtained from the ratio of the amplitudes of the CMB acoustic peaks and from large scale structure studies. Now the issue in BBN is to understand if and why the other (^{4}He and ^{7}Li/Be) light element abundance yields predicted by BBN at the deuteron abundance-selected baryon number do not agree with their observationally-determined primordial abundances. Any significant lepton number in the universe, beyond that required for overall charge neutrality, would have to reside in the seas of neutrinos left over from the epoch with $T > 1$ MeV when neutrinos and matter were in thermal equilibrium. Indeed, our most stringent constraints on the lepton numbers come from BBN considerations (especially the ^{4}He abundance). Future insights into or constraints on lepton numbers obtained with, for example CMB anisotropy measurements, could be telling us about these lepton numbers.

Finally, in the last several years many in the neutrino astrophysics community have pointed out that active-

active coupled with active-sterile neutrino transformation can result in lepton number generation in the early universe. In fact, without a great deal of fine tuning the four-neutrino schemes advanced to fit simultaneously the solar, atmospheric, and LSND neutrino oscillation data are at odds with the usual picture of BBN and the observationally-inferred light element abundances. Does this mean that the LSND data does not pertain to neutrino flavor oscillations, or does it imply that there is a pre-existing lepton number in the universe, or does it mean that the mass/mixing scheme is "picked out" by the abundance pattern and BBN considerations. We do not as yet know enough to answer this question. These sorts of questions do, however, highlight the importance of the upcoming mini-BooNE experiment, which will test the LSND results.

V. HIGH-ENERGY NEUTRINOS

During the last decade, the first steps were taken to tap into the potential wealth of information provided by high energy neutrino messengers. Typically, models of high energy neutrino production invoke interactions between a relativistic beam of accelerated hadrons and a variety of target materials. Born in weak interactions, neutrinos carry information from the heart of the most explosive and turbulent sources that populate the sky. Unlike charged particles, neutrinos are unaffected by large scale magnetic fields, independent of energy. At the energy frontier, neutrinos are the only known particle with the capability to penetrate thick cocoons of material near the source and the only particle unhindered by diffuse intergalactic photon backgrounds. High energy neutrinos provide unambiguous evidence for cosmic acceleration of protons and nuclei, and point back to the location of the accelerator.

The scientific agenda has focused on the search for the source(s) of the highest energy cosmic rays, but high energy neutrino detectors may contribute to topics of broad interest to particle physics and cosmology. Plausible theoretical models of Gamma Ray Bursts (GRBs) or Active Galactic Nuclei (AGNs) have demonstrated that both classes of sources are capable of generating the highest energy cosmic rays, but more exotic mechanisms assert that the decay of remnant particles from topological structures in the early universe are responsible. Neutrinos with approximately EeV energies are generated by the Greisen-Kuzmin-Zatsepin (GZK) cutoff. The detection of these neutrinos represents an important milestone in neutrino astronomy. It would help to determine the distribution of the sources and constrain the identity of the constituent particles at the energy frontier. Moving closer to home, neutrino astronomy may aid the search for sources of the galactic cosmic rays . No conclusive evidence for hadron acceleration has been found thus far, but it is possible that the sites include supernova remnants that are known to emit TeV-energy gamma rays. The search for Weakly Interacting Massive Particles (WIMPs), possible constituents of the cold dark matter, rounds out this brief overview of science objectives. If WIMPS populate the halo of our galaxy, they could be captured in the sun or earth, where they would annihilate occasionally into high energy neutrinos. The rate depends on the details of the model. A widely discussed WIMP candidate is the lightest neutralino in Minimal Supersymmetric Models. High energy neutrino telescopes (HENTs) complement direct search detectors by reaching good sensitivity at high neutralino masses, typically in excess a few hundred GeV. HENTs can probe regions of parameter space that allow large branching fractions to W and Z bosons, but they reach background limited operation due to irreducible contamination from atmospheric neutrinos. The broad diversity of the science missions outlined for the HENT programs provide a revealing example of a mutually beneficial cross-disciplinary effort between astrophysics and particle physics.

A variety of techniques are being explored to address the wide range of potential scientific objectives outlined above. The current generation of HENTs use the same optical cherenkov techniques originally pioneered to search for proton decay, except that HENTs must be constructed and operate in remote, uncontrolled, and often hostile environments. The long sought dream of constructing a telescope with an unrestricted, high sensitivity view of the neutrino sky has been realized by the first extended operation of the AMANDA (B10 and II) and NT-200 detector arrays. AMANDA is embedded within optically transparent ice 1-2 kilometers beneath the South Pole, and NT-200 is located 1 km beneath the surface of Lake Baikal, Russia. In addition, the NESTOR and ANTARES collaborations have made considerable progress toward their goal to construct HENT arrays in the Mediterranean Sea. Collectively, these detectors have the capability to search for astrophysical neutrino sources over the entire sky and measure fluxes which are several orders of magnitude lower than published limits, at least for some of the high priority physics objectives. For example, these detectors can observe fluxes that are approximately a factor 10 below current limits of TeV-PeV neutrinos from point and diffusely distributed sources, and ANTARES is expected to achieve 0.2 degree pointing resolution. They have the capability to detect diffuse EHE emission from AGN, GZK interactions, topological defects or Z-bursts that is more than a factor of 100 below current limits. Gamma Ray Bursts provide a special opportunity. External triggers from satellites reduce the background by many orders of magnitude compared to the more ambitious science goals.

The low level of optical noise present in the deep Antarctic ice is utilized by the AMANDA-II collaboration to monitor the galaxy for Supernova. Another important objective involves the search for weakly interacting particles (WIMPs) from the core of the sun or earth. Current generation HENTs should probe fluxes that are ultimately constrained by intrinsic backgrounds from atmospheric neutrinos.

To summarize, the groundbreaking capabilities of current HENT programs demonstrate the versatility and appropriateness of the optical cherenkov technique. Given this success, it is natural to consider straightforward expansion to larger scales. The planned extensions to AMANDA-II (called IceCube) and the water-based neutrino detectors will continue to probe for weaker sources by increasing the characteristic scale of the instrumented volume to 1 km3. At an estimated cost of $250M, IceCube is expected to achieve an order of magnitude improvement over its predecessors for physics objectives that are not limited by intrinsic contamination by atmospheric neutrinos. In particular, the search for transient point sources (GRBs, SNa, highly variable AGN, etc.) will strongly benefit from the increased size because backgrounds are relatively small. Moreover, if the current generation detectors are successful at finding astrophysical sources, then the next generation may be sufficiently sensitive to observe ν_τ. The discovery that neutrinos oscillate implies that cosmic beams will contain equal numbers of all neutrino flavors. Unlike the other flavors, nu-tau can penetrate the earth at all energies because the nu-tau charged current interactions create a tau lepton which then decays back to a tau neutrino before losing all its energy. The energies typically degrade to the point where the earth becomes transparent to all neutrino species. Thus, the detection of nu-tau requires the signal to be extracted from significant background generated by the (presumably) larger flux of other flavors at the transparency energy. At 10 PeV, nu-tau interactions produce a background-free signature called the double-bang. Since this energy is above the transparency energy of the earth, these neutrinos must arrive from upper hemisphere. The extent to which this can be exploited depends on the effective detection volume, which for volumetric array architectures (ie, architectures with a quasi-uniform spacing between strings of sensors) is constrained by phase space considerations. Finally, despite the presence of irreducible backgrounds, kilometer scale arrays should reach regions of SUSYparameter space not accessible to other methods if the systematic errors can be kept under control.

The total power budget and energy spectra of sub-PeV cosmic rays is conventionally explained by the process of first-order Fermi acceleration from shocks initiated by supernova in the galaxy. However, naive dimensional analysis shows that this explanation runs into difficulties for the observed cosmic particles at higher energies. A feature at 10^{18} eV in the cosmic ray spectrum provides additional evidence that a new acceleration mechanism may be required explain the origin of cosmic rays at the highest energies. Extra- galactic sources such as AGN or GRBs may plausibly generate cosmic rays with the maximum observed energies, but the mysteries deepen as the energies approach 10^{20} eV. A realistic acceleration model has yet to be devised to generated hadrons with such energies. Most potential cosmic accelerators contain magnetic fields that are too weak, or the acceleration region is too small, or the containment time is too short. If the sources of extremely energetic cosmic rays are extragalactic and the particles are hadronic, then they interact with the cosmic microwave background photons on relative short distances ($\approx$ 50 Mpc). Two observations consequences ensue: first, the collisions will reduce the initial energy of the particle to $\approx 5 \times 10^{19}$ eV, independent of its initial value, and second, EHE neutrinos are produced. These so called "GZK neutrinos" provide a strong motivation to search for EHE neutrinos with existing arrays and to develop new devices with improved sensitivity. The angular distribution of cosmic rays presents another difficulty for theoretical interpretation. At these energies, the deflection from galactic magnetic fields is very small so the directions of measured events should point back to the sources of acceleration. For example, galactic accelerators should be correlated with the galactic plane. Unfortunately, no obvious correlation with energetic sources pops out of the sky maps, suggesting that the sources that accelerated the particles are no longer sufficiently active to warrant attention, or the distance limitations imposed by interaction with the microwave background is not relevant.

The lack of detailed acceleration models, and the possible overabundance of events above 10^{20} eV (which fail to point to obvious sources), has led to speculative alternatives for EHE cosmic ray production. They typically involve the decay of supermassive particles, the decay of primordial black holes, or the decay of topological defects generated in re-heating phase after inflation.

As the energies of the neutrinos increase to 10 PeV or beyond, miniscule fluxes and attenuation by the earth drive the main experimental challenges. For example, neutrinos generated by the GZK mechanism require apertures in excess of 100km^3/sr, but optical cherenkov neutrino telescopes can barely reach the most optimistic predictions. Several new concepts are being developed to boost the sensitivity at the highest energies. The most widely discussed ideas involve calorimetric detection of cascades. The Pierre Auger Project detects EHE neutrinos via horizontal air showers and tau-neutrinos via showers initiated by tau-leptons emerging from distant mountains or from interactions that graze the surface of the earth. The detection of coherent radio emission from neutrino-initiated cascades (known as the Askaryan effect) provides another possibility to extend the sensitivity and several prototype experiments have exploited this signature. The RICE detector consists of an array of antennas buried in the ice at the South Pole, and the GLUE project uses two radio telescopes at the Goldstone facility in California to search for EHE emission from the surface of the moon. Recently, a balloon-borne radio detector called ANITA has been proposed to search for GZK neutrinos. The radio signals are detected by an antenna that circles about the edge of Antarctica at an altitude of 35-40 km. All the radio-related efforts were given a shot in the arm recently by experimental confirmation of the Askaryan effect by experiments performed at SLAC. Over the longer term, space-based telescopes are planned to extend the search for high energy neutrinos and cosmic rays using a technique pioneered by the Fly's Eye collaboration. At the energy frontier, the OWL concept, and possibly the precursor project called EUSO, should be able to lower the minimum detectable flux by another 1-2 orders of magnitude by measuring air fluorescence over a circular patch of the atmosphere as large as 3000 km in diameter.

The Super-Kamiokande detector anchors the low energy boundary of high energy neutrino astronomy. It was the first to provide a directional measurement of solar neutrinos in real time and confirmed the solar neutrino deficit. It discovered neutrino oscillation using atmospheric neutrinos. A conceptually straightforward extension of the Super-Kamiokande detector, called UNO, was discussed in detail at this workshop. Although primarily designed to search for proton decay, a detector with roughly 20 times the fiducial mass of Super-Kamiokande can collect a sample of 105 neutrino interactions from a supernova burst near the galactic center and a clear signal from Andromeda, at a distance of 1 Mpc. Also, UNO-scale instruments can search for astrophysical point sources of neutrinos, and WIMP dark matter in an energy range that is difficult to cover efficiently by the coarsely pixelated underwater or under-ice HENTs. Recent theoretical effort has been invested to calculate the flux of neutrinos at GeV energies from GRBs and Supernova which provides added incentive for the proponents of these facilities .

HENTs are developing during an era of exciting discoveries in related areas of particle astrophysics: the detection of rapidly varying multi-TeV gamma ray signals from AGN, the discovery the GRBs are extremely distant and they may emit TeV photons as well, the still controversial report of a large overabundance of cosmic rays above 10^{20} eV, and strong evidence for neutrino oscillation from Super-Kamiokande and SNO data. At the moment, the hadronic sky is being probed with the first dedicated instruments to search for sources of high energy neutrinos. They constitute bold, essential steps toward the realization of multi-messenger astronomy. New facilities with impressive capabilities are now under construction (Auger, ANTARES, NESTOR) or proposed (IceCube, KM3, ANITA, MONOLITH) or planned (OWL, UNO). If history is a guide, there will be surprises in store as these detectors begin to survey the great canvas of the unknown.