

Research (October 1992- September 2001)

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Introduction

My research program investigates questions in the interdisciplinary fields of cosmic rays, particle physics, and high-energy neutrino astrophysics. Recently, I have promoted the concept of multi-messenger astronomy to tackle some of the toughest issues in particle astrophysics. This idea has been adopted in a report by the sub-panel for Particle, Nuclear and Gravitational Wave Physics of the Astronomy and Astrophysics Survey Committee, which is formed every decade. Astronomy is usually aided by instrumentation sensitive to electromagnetic radiation (photons), but this decade has witnessed the construction of new instrumentation sensitive to alternative information carriers - gravity wave interferometers and high energy neutrino telescopes. The former probes physics that involve strong gravity such as the coalescing of black holes while the latter directly investigates the details of hadronic processes in the cosmos. Neutrino detection provides unambiguous proof of hadron acceleration, and therefore offers the opportunity advance our understanding of some of the most violent and energetic phenomena in the Universe. Cosmic rays are particles - predominantly protons and other stable nuclei - accelerated to extraordinary energies by astrophysical processes. Some cosmic rays arrive on the earth with macroscopic (Joules) energies, yet no firm explanation for an accelerating mechanism is known. For particles with energies in excess of 10^{15} eV, the acceleration mechanism, the location, quantity, and identity of the source, and the species of the particle are all unknown. For cosmic rays with energies between 10^9 eV to 10^{15} eV, we believe galactic particles are accelerated by first order Fermi processes in Supernova remnants (SNRs), but even this story has gaps in the plot. Though direct observational evidence for this mechanism is scarce, at least one SNR emits photons at energies that require electron acceleration to 10^{14} eV. Unfortunately, the common acceleration models fail to replicate the measured photon energy spectrum, and many of the SNR that should generate high-energy photons, do not. Early in the decade, my research program concentrated on direct measurements of the cosmic rays using balloon-borne instrumentation to assess acceleration and propagation models and potentially search for unexpected, primary sources of antimatter. For example, it was thought that anti-particles could arise from the annihilation of dark matter in the galactic halo. The extra source of anti-particles would distort the spectral shape expected from the ordinary nuclear interactions that normally occur between galactic cosmic rays and interstellar matter.

During the latter half of the decade, my group at UCI has investigated and developed experimental techniques that can observe the neutrino messenger with greatly improved sensitivity. Since 1997, the AMANDA (Antarctic Muon and Neutrino Detector Array) High Energy Neutrino facility has searched for astrophysical sources of high energy neutrinos, and we have recently reported scientific results in *Nature* and at the International Cosmic Ray Conference held in Hamburg, Germany last August. Members of my group (John Kim and Scott Young) have taken the lead in searching for point sources of high-energy neutrinos. Recently, Stephan Hundertmark and Lisa Gerhardt have developed an analysis technique to search for extremely high energies neutrinos in excess of 10^{17} eV (ref 132). At these energies, neutrinos may arise from interactions of highest energy cosmic rays on cosmic microwave background photons, or from more exotic mechanisms such as Z-bursts or the decay of topological defects created in the early Universe. The latter mechanisms were created, at least partially, to explain the still contentious observation of cosmic rays with energies in excess of 10^{20} eV. It has long been thought that such energies would not be observable if cosmic rays with energies above the "ankle" were ordinary nuclei and accelerated by extragalactic sources. Even if cosmic rays were created with energies above 10^{20} eV, they would rapidly lose their energy by interactions with the cosmic microwave photons. Given the difficulty of the cosmic ray measurements at extreme energies, it is not surprising that different groups obtained different results. For example, the U.S. Hi Res experiment measures an energy spectrum consistent with a high energy cutoff, whereas the Japanese experiment, AGASA, reports more than 15 events with energies in excess of 10^{20} eV. Neutrinos may help to clarify the situation because they can travel through the Universe unimpeded by intervening material, photon fields, or by intergalactic magnetic fields, which complicate the interpretation of cosmic ray data.

My role in the AMANDA project has evolved throughout the decade. We began as a very small group of individuals who wanted to investigate the optical properties of deeply buried ice in Antarctica. AMANDA expanded into an international collaboration which includes approximately 90 authors from 15 Universities throughout the US and Europe. For the past several years, I have been elected Co-Spokesperson, charged with oversight of detector operations and management of scientific output. I have

written several review articles (ref 96 and ref 42), including the Nobel Symposium on Particle Astrophysics (ref. 96), and most recently for the SLAC Summer Institute (ref 120). These papers traced the history of the subject of high energy neutrino telescopes, summarized the scientific objectives of these facilities, and surveyed the experimental status of the field. I am currently serving on the High Energy Neutrino Advisory Panel (HENAP), which was created by IUPAP. We are charged to evaluate the scientific and technical merit for the construction of a kilometer scale neutrino telescope in the Mediterranean Sea.

Currently, my group at UCI includes two postgraduate research physicists (Yuan Yan and Stephan Hundertmark), several graduate students (Lisa Gerhardt, Kyler Keuhn, and Dave Ross – Masters program), and one undergraduate (Misato Hayashida).

HEAT (High Energy Anti-matter Telescope) balloon program

The primary science objective of the HEAT project is to measure the energy spectrum of positrons in the cosmic radiation between 5 GeV and 50 GeV. Data collected during the ascent phase of the balloon flights, typically collected for calibration purposes, have played an important role in solidifying the evidence for neutrino oscillation first reported by the SuperKamiokande collaboration. I was the first to recognize within the HEAT collaboration that ascent data could investigate the reliability of the Monte Carlo-based simulation programs which calculate the atmospheric neutrino fluxes because the neutrino production in the atmosphere is intimately connected with muon (μ) production. A measurement of the μ^+/μ^- ratio as a function of depth in the atmosphere was first reported by the HEAT collaboration in 1995 (ref 56). Since then, these results have been refined and extended (ref 84, 92). These results provide evidence that the computer calculations are reliable, and suggested that further analysis of absolute fluxes of muons would provide valuable insight to assess the relative importance of computational and physics-related details of the simulation programs. This topic was the centerpiece of the thesis of Eric Schneider, and he was awarded the Sylvia Reines Nobel Spouse Award from the UCI Town and Gown organization. This work has continued by other collaborators who have taken up the gauntlet. Recently, (ref 109) we have shown that new fully three-dimensional simulation programs agree with the measured data to excellent statistical accuracy, except near the top of the atmosphere. Fortunately, the uppermost regions of the atmosphere contribute little to the flux of atmospheric neutrinos. The previous 1D codes were inaccurate at the 20-50% level due to selection effects since 1D propagation codes always generate particles with a minimum path-length.

Cosmic ray positrons are created as secondary particles in proton-proton collisions via pion production and subsequent decay. If this is the only mechanism for positron production, then the energy spectrum should track the well-known proton energy spectrum. Prior to the construction of HEAT, data on the positron spectrum exhibited an unexpected increase at energies beyond 10 GeV. Several explanations were postulated for this spectral feature by introducing new primary sources of positrons such as (1) positron-electron pair production by gamma rays in the strong magnetic fields of pulsars, or (2) pair production from the annihilation of dark matter in the galactic halo. Our first measurement of the flux of cosmic ray positrons, reported in Physical Review Letters (ref. 55), does not indicate a major deviation from the expected results. In particular, we saw no evidence for the dramatic rise in the positron fraction at energies above 10 GeV. However, this and subsequent flights of the HEAT payload have revealed that we cannot exclude the possibility of a few percent admixture of a primary component (ref 79 82, 90, and 97) due to a small, but statistically significant, discrepancy between model predictions and data.

My group's hardware responsibility within the HEAT collaboration was to design, construct, calibrate, and integrate an electromagnetic calorimeter into the HEAT payload. It was designed to reject 98 percent of the hadrons (since protons and helium nuclei are the dominant components of the cosmic rays) and measure the positron and electron energies to an accuracy of 10%. The design of the calorimeter had to incorporate several unusual constraints - it had to fit within a very small physical volume, function in magnetic fields as large as 1 Tesla, withstand accelerations to 10g's, require less than 50W of power, and provide clean timing signals for time-of-flight analysis. Our paper published in NIM demonstrated that the electromagnetic calorimeter functioned reliably and performed according to expectation (ref. 77).

AMANDA high energy neutrino telescope

Development of the AMANDA high-energy neutrino telescope was overwhelmingly motivated by its potential for scientific discovery. High-energy neutrinos provide us with the first tool with the capability to directly probe into the core of energetic sources, which are often obscured by surrounding matter. While intervening matter limits the utility of photon messengers, which are often highly processed by the time they exit the source, it creates few difficulties for high energy neutrinos which freely stream through this material. Neutrinos are a “natural” messenger to probe the distant reaches of the universe because no known mechanism exists that generates significant attenuation. On the other hand, high-energy photons interact with the cosmic infrared background and charged particles interact with cosmic microwave background if their energies are sufficient to reduce the impact of galactic magnetic fields to negligible levels. What I find most intriguing is the possibility to use neutrino messengers to probe particle physics with unprecedented sensitivity. The power of multi-messenger astronomy is beautifully illustrated by the example of Gamma Ray Bursts (GRBs). Bahcall and Waxman have pointed out that if neutrinos are emitted from GRBs, then the most likely mechanism of neutrino production should create negligibly few ν_τ at the source. We could confirm neutrino oscillation by the presence of tau-neutrinos, but this is perhaps not so interesting in light of the recent SNO measurements. However, by measuring the difference in arrival time between photons and neutrinos with a precision of a few seconds, we can test special relativity or the weak equivalence principle at a precision of parts per million. If MILAGRO and AMANDA contemporaneously observe high-energy photons and neutrinos (respectively), the combined data create opportunities beyond what either can accomplish separately.

The experimental requirements for a successful design of a high energy neutrino telescope have been known since the early 1960's. Enormous volumes must be instrumented to detect the small fluxes of astrophysical neutrinos expected from most models. To escape the prodigious background from cosmic-ray induced muons, the detector had to be buried beneath several thousand meters of overburden. The enormous size of the detector disfavored the use of manmade caverns, which forced experimenters to consider only natural media such as deep, ocean water or transparent ice. Francis Halzen and John Learned first suggested that Antarctic ice might be a suitable medium if the optical scattering and absorption lengths were sufficiently large. Once I heard this idea, I designed a device to test the optical properties. Moreover, it was clear to me that Antarctic ice has many advantages over ocean designs (contrary to popular opinion at that time). First, the solid platform permitted far more flexibility in the architecture and technology of the neutrino telescope, and so I implemented a robust, redundant design with no possibility for single point failures. In particular, my work on the PBAR antiproton detector convinced me that 5ns timing could be achieved over electrical cables of several kilometers in length. Therefore, there was no need to digitize in the remote underground environment. Fast analog signals have never been used in this way, and it required several innovations. First, I worked with Hamamatsu to design a high gain PMT that could send unamplified analog signals to the surface electronics. The goal was to keep all of the most failure-prone electronics on the surface where they could be repaired or replaced. Second, the time that was required to transport signals from the sensor to the electronics had to be measured with an accuracy of nanoseconds, or a fractional precision of 0.1%. We at UCI developed a calibration system that was based on surface lasers coupled to optical fibers.

Several other practical considerations suggested that designs utilizing polar ice compete favorably against deep water detectors in oceans or lakes. The design of the AMANDA array took advantage of the existing infrastructure in the US Antarctic Program. Aircraft were able to transport large cables and delicate optical sensors to the pole with great reliability and professionalism. Power, housing, and hot water drills were available at the Amundsen-Scott Research Station, as well as year round operation with skilled crews. It was clear to me that Antarctic Ice offered the first real possibility for a practical design of the ideas first expounded in the early 1960's.

We have started to release scientific results from the first year of operation of the completed 10 string array, which we denote AMANDA-B10. Due to the fact that atmospheric neutrinos are our only guaranteed source of signal events, we initially concentrated on extracting this signal. This challenge is difficult because atmospheric neutrinos are not very abundant at the energies of interest to us and they are diffuse - nearly uniformly distributed on the sky - similar to the distribution of uninteresting background events generated by wrongly reconstructing the direction of ordinary down-going atmospheric muons. We developed a maximum likelihood analysis that properly accounts for the timing pattern of photon arrival

times and a suite of selection criteria that identify those events with reliable trajectory information. The details of this analysis technique have been published (ref. 99 and ref 117). Our paper published in Nature this year outlined the arguments that demonstrate that AMANDA has achieved all of the technical objectives for neutrino astronomy. This paper was the culmination of several years of analysis effort, and it was popular with the press.

The efficiency of the analysis of the full B10 array has evolved rapidly. Early analysis of six months of data from 1997 produced a sample of 17 events (ref. 103) which were distributed on the sky as expected from our simulation programs. Geometric properties, like event topology, were also consistent with the atmospheric neutrino hypothesis. Simulation studies of background indicated that our selection criteria were sufficient to eliminate inaccurately reconstructed events. As the calibrations, filtering, and reconstruction procedures are iterated and refined, we have increased the number of events in the sample to approximately 50, nearly a 3-fold increase. Thus far, the sensitivity of the detector that results from the atmospheric neutrino analysis exhibits a large variation as a function of zenith angle. The angular uniformity of the detector was dramatically improved by John Kim and Scott Young (members of my group at UCI) who developed an energy variable based on the average "brightness" of the muon (ref. 112). The development of this technique and subsequent analysis was greatly facilitated by the UCI supercomputer center, AENEAS. By concentrating on potential point sources with hard spectra, we achieved an effective area of 10,000 m² over a 30 degree patch of the sky, and more than 5,000 m² to within 30 degrees of the horizon. These performance characteristics are close to the canonical parameters anticipated by the AMANDA-B10 proposal. An all-sky search for point sources was reported by J. Kim at the ICRC 99 in Salt Lake City (ref. 112), and by myself at more recent neutrino and cosmic ray conferences (ref. 116, 118), and now published in the UCI dissertation of Scott Young. With only 20% of the data on tape, we reported preliminary flux limits that are comparable to the best existing limits for any part of the sky, and far better than the existing limits for the region of the sky that is probed with maximum sensitivity. A paper detailing the point source analysis is under internal review by the collaboration, and expected to be submitted to Ap.J. by November, 2001. In this paper, we describe the systematic errors in the angular dependence of the sensitivity and angular resolution.

We also recently reported the best limit on the flux of relativistic monopoles (ref. 105, 129), and demonstrate our capability to monitor the sky for supernova (ref. 114, 128). AMANDA can also search for WIMP dark matter. Dark matter particles are gravitationally trapped in the center of the earth and annihilate with each other to produce high-energy neutrinos. While our results are not yet competitive with existing limits, the potential of this technique as we expand the array to kilometer dimensions is illustrated in ref.100.

We have produced a very detailed set of publications on the optical properties of the South Pole ice (ref.78, 102). Absorption lengths can exceed 200m for blue and UV light, an astonishingly large value. Scattering properties have been mapped from 800m to 2300m. Near the top, air bubbles trapped in the ice are responsible for scattering optical photons. The scattering length increases as the bubbles disappear with increasing depth. Below 1400m, dust, soot, and acids provide an upper limit to the scattering length. In the region of AMANDA-B10, the average scattering length is 25m but varies with depth. Ice ages and interglacial variability observed in ice cores are clearly observed in our data. This work demonstrates that deep Antarctic ice is suitable for large neutrino detectors, such as the planned IceCube facility (ref.107). These results are the product of widespread internal cooperation within the collaboration. UCI personnel were responsible for developing the interstring calibration techniques using short-duration optical pulse generated by a surface laser. This data provided a crucial baseline for assessing various optical parameters. We were responsible for generating and insuring the suitability of the data. Personnel at UC-Berkeley analyzed and interpreted this data, which show good agreement with models of optical properties of polar ice developed by Buford Price and Yudong He.

As the collaboration has grown in size, internal review of scientific publications has grown more elaborate, thus improving the final product at the cost of additional delays during the implementation of formal review procedures. We expect that many of these results now reported at international scientific conferences will be published within the upcoming year. This is similar to the recent publication of AMANDA-B4 analysis (ref. 99) in Astroparticle Physics after preliminary results were reported at the International Cosmic Ray Conference in 1997 (ref 85, 86, 87, 88).

In January 2000, we completed the second phase of construction, denoted AMANDA-II, that expands the AMANDA-B10 array by another 9 strings of high performance optical sensors. Francis Halzen (UW-Madison) and I are the PIs on this proposal. AMANDA-II will increase the angle-averaged sensitivity by a factor of 3 over B10 and it greatly improves the effective area near the horizon (ref. 124, 135). In fact, it has the potential to achieve background-limited operation for many scientific objectives such as the search for diffusely distributed sources and WIMPs from the sun and earth (since the background of atmospheric neutrinos is intrinsically identical to expected signal, this is the best we can do). Just as important, it simultaneously serves as a research and development tool for future expansion. Three years ago, we deployed three strings containing optical and electrical components to a depth of 2350m. The instrumented length of the strings extended over the bottom 1200m, thus demonstrating the technical capability to install strings with kilometer dimensions.

My group has taken the lead in the design and fabrication of the AMANDA detector. In 1993, members of my group (Rodin Porrata and Pat Mock) and I designed the initial production string of sensors for AMANDA-A, and then acted as consultants for the construction of the remaining strings. This responsibility continues today as we finalize the construction of a prototype string of optical sensors which utilize laser diodes to transmit analog signals over two kilometers of optical fiber to surface electronics designed at DESY-Zeuthen. The goal was to maintain the relative simplicity and reliability of the successful earlier designs while achieving superior performance characteristics that include dynamic range, double pulse resolution, and cable-induced cross-talk. These sensors were deployed during January 2000, along with several other candidate technologies for the planned kilometer scale detector, which we call IceCube. The design using laser diodes has been refined over several seasons of practical operation where we have evaluated mechanical robustness, thermal and temporal stability, and other issues. We were sufficiently confident in the basic level of performance that it was incorporated into the reference design for the IceCube proposal. It remains a viable alternate technology in the event that the more capable digital technologies fail to meet requirements.

Planning for IceCube was jumpstarted at a workshop held at UC-Irvine in March of 1998. Originally envisioned to create an intimate working environment for several dozen physicists, the workshop drew more than 80 people from the Europe and the US. The nearly overwhelming response graphically demonstrated the widespread interest by the community to open a new window on the Universe. Since then, the IceCube project was proposed in November of 1999 and approved by the National Science Board this year. Since the IceCube construction is expected to last until the end of the decade, it is important to understand the capabilities of the instrument at intermediate stages of the construction. Several students (a summer REU student Justin Domke and an UCI undergraduate, Misato Hayashida) and I have studied the performance of a composite detector consisting of the first 16 strings of the IceCube array and AMANDA-II. The deployment of the first 16 strings is planned to start in January 2004 and finish by January 2005, which is a relatively short time scale. We find that such a configuration achieves a sensitivity that is nearly half of the final IceCube design, which indicates that leading-edge science can be extracted during the extensive construction phase of IceCube.

AMANDA was designed to inaugurate the field on neutrino astronomy. My colleagues and I have spent more than five years developing nearly all aspects of the technique (construction, calibration, data collection and analysis) and we have demonstrated its technical capabilities and advanced sensitivity. The extent to which the current generation of neutrino telescopes will address scientific questions relies on some cooperation by Nature (not the journal). Congressional leaders recognize the AMANDA project as an important contribution to the national science portfolio. The house appropriations bill H.R.2620¹ (<http://thomas.loc.gov/home/approp/appover.html>) states

¹ House Committee Report - House Rpt. 107-159 - DEPARTMENTS OF VETERANS AFFAIRS AND HOUSING AND URBAN DEVELOPMENT, AND INDEPENDENT AGENCIES APPROPRIATIONS BILL, 2002

" This project, **building on the successful AMANDA demonstration**, is designed to more fully develop knowledge of the origins of the universe as well as the fundamental nature of physical matter using its unique polar telescope. "

The senate bill contains similar language (<ftp://ftp.loc.gov/pub/thomas/cp107/sr043.txt>)

"The Committee encourages the Foundation to move forward with the South Pole Station Antarctic Muon and Neutrino Detector (AMANDA) project to its next phase, called IceCube. The Committee is advised the National Science Board has recently approved this project. **AMANDA's technological approach has proven successful at detecting high-energy atmospheric neutrinos.** Continued development is expected to lead to a new era in astronomy in which scientists will have unique opportunities to analyze some of the most distant and significant events in the formation and evolution of the universe. "