LATEST RESULTS FROM AMANDA

P. B. PRICE (for the AMANDA Collaboration †)
Physics Department, University of California, Berkeley, CA 94720

After a brief scientific motivation for an ultrahigh-energy neutrino observatory in deep South Pole ice, I report on the successful completion of the 10-string AMANDA-B at 1.5 to 1.9 km depth, which follows the earlier completion of the 4-string AMANDA-A at 0.8 to 1 km depth. I then discuss the optical properties of South Pole ice, which govern the performance of AMANDA, and summarize progress in developing a computational filter for enriching the fraction of data in upward-going neutrinos and a maximum-likelihood line fitter for determining muon trajectories in AMANDA-B. Steps toward an observatory of effective volume 1 cubic kilometer are mentioned.

1 Scientific Motivation

Papers at this Moriond Conference stressed the need to use the entire arsenal of probes -- cosmic ray particles, photons, neutrinos, and gravitational waves -- to understand the sources and mechanisms for producing the highest energy phenomena in the Universe. Two types of astronomical accelerators -- blazars (Active Galactic Nuclei oriented with a jet pointing toward the observer) and gamma-ray bursters (GRBs) -- were discussed at great length. In the "proton blazar" model, shock acceleration of protons to energies above 1 EeV in a blazar occurs in blobs of plasma in a jet normal to the accretion disc around a ~10^9 solar mass black hole [1]. Neutrinos with typical energy of PeV and high-energy gamma rays are produced in hadronic interactions of the protons. Direct detection of neutrinos would provide support for this model. Two relatively nearby blazars -- Markarian 421 and Markarian 501 -- are known to emit gamma rays up to several TeV. A plausible explanation for failure to detect TeV gamma rays from more distant blazars is that they are absorbed in passing through a universal infrared radiation background. Neutrinos would of course not be absorbed.

Gamma-ray bursters, now generally believed to be at cosmological distances, emit gamma rays typically of MeV energy but occasionally extending up to many GeV, and none have yet been proven to repeat. The standard model is the inspiralling and coalescence of two orbiting neutron stars, with production of an ultrarelativistic fireball responsible for the gamma rays [2]. Hadronic acceleration mechanisms may lead a burst of cosmic rays, gamma rays, and neutrinos in bursters [3]. An entire solar mass is converted into kinetic energy of the fireball (possibly into a jet) and into neutrinos, and only about 10^{-3} into gamma rays. Some theorists predict thermal (multi-MeV) neutrinos; others predict both cosmic rays and neutrinos with power-law energy spectra extending to >10^{14} eV [3]. For neither AGNs nor bursters is it known whether the gamma rays are produced in electromagnetic or hadronic processes. Given a collecting volume ~1 km^3, AMANDA might be able to detect neutrinos and thus settle this issue, as well as estimate fundamental quantities such as neutrino mass.

A third topic, of great importance to particle physics, concerns the possibility that the dark matter in the universe consists of supersymmetric particles called neutralinos. AMANDA could look for neutrinos from the center of the earth or sun that would signal the annihilation of neutralinos gravitationally trapped in these objects. Even a version of AMANDA as small as 0.01 km^3 will have discovery potential for some regions of parameter space.

Of course, the most exciting prospect is for discovery of entirely unexpected phenomena.

2 AMANDA Concept

A priori, reasons for deploying AMANDA in deep ice at the South Pole included:

- NSF infrastructure, including drilling team, on-site machine shop, and laboratory building;
- continuous accessibility for > three months per year;
- no background light (neither ^{40}K decays nor bioluminescence);
- short cables and no need for electronics at depth;
- transparency of ice to radio Cherenkov emission.

A posteriori, additional reasons emerged:

- superb optical clarity in blue and near-UV where quantum efficiency of PMT is optimal;
- PMT noise rate only $\sim 10^3$ Hz;
- only six days to drill and instrument a string of PMTs to depth of 2 km;
- array expandable to ~ 1 km^3 as funding permits.

3 AMANDA A: the Exploratory Phase

In 1993-94, the hot-water technique was used to drill four holes to 1 km depths and to deploy strings instrumented with 8-inch PMTs from 0.8 to 1 km at vertical intervals of 10 m. 73 of the 80 PMTs survived refreeze of the melt water and have been operating with no failures for the last three years. At a gain of 10^8, the Thorn EMI PMTs run at a typical noise rate of ~1500 Hz.

With a YAG laser in a laboratory at the surface nearly directly above AMANDA, we mapped the absorption and scattering lengths as a function of depth and wavelength from 410 to 610 nm by sending nanosecond pulses down optical fibers to emitter balls and measuring the distributions of arrival times at various PMTs. The time distributions could be fitted well with an analytic function describing three-dimensional random walk (scattering) with absorption. The results were startling:

• The absorption length, λ_a, in the blue region is an order of magnitude greater than had been previously claimed for laboratory ice and for purest water. λ_a reaches values of nearly 300 m in the blue at 800 m and declines somewhat with depth due to an increase in concentration of insoluble dust, which contributes to both absorption and scattering.

• The effective scattering length, $\lambda_e = \lambda_s/(1 - \langle\cos\theta\rangle)$, is far smaller than we (and glaciologists) had expected. This stimulated us to develop a diffusion model of the rate of conversion of air bubbles into solid air-hydrate crystals [4]. The model quantitatively fit microscopic measurements of bubble sizes *vs* depth for Vostok and Byrd Station, and fit our rate of increase of λ_e with depth (from ~40 cm at 830 m to ~80 cm at 970 m) in South Pole ice. This confirmed that residual bubbles cause the scattering and led to the prediction (subsequently verified) that the phase transformation from bubbles to air-hydrate crystals would be complete at a depth ~1450 m.

The presence of bubbles prevents us from determining muon trajectories in AMANDA A. However, in the process of studying the diffusive propagation of light, we discovered two important ways to use AMANDA A, and by extension, also AMANDA B.

• With a special trigger we are able to search continuously for a flood of MeV neutrinos that simultaneously increases the noise rates in all PMTs. A stellar collapse similar to supernova 1987A at a distance of 8 kpc would yield about 100 excess counts per PMT within 10 seconds. Equally exciting is the possibility of seeing a flood of neutrinos accompanying a gamma-ray burst [3].

• We are using AMANDA A as a test-bed for accurate measurement of the total energy in an electromagnetic cascade such as would result from interaction of an electron neutrino. The same concept, scaled up to 1 km^3, will allow us to measure the energy of ultrahigh-energy cascades, from which light propagates diffusively on length scales of hundreds of meters.

4 AMANDA B: Now a Working Neutrino Observatory

During the 1995-96 season we drilled four holes to depths of ~2 km and deployed strings instrumented with Hamamatsu 8-inch PMTs at vertical intervals of 20 m from 1.55 to 1.95 km. 79 of the 86 PMTs survived refreeze; all of them are still operating, giving us a mean time between PMT failure of > 300 years for AMANDA A + B. These PMTs, at a gain of 10^9, have a remarkably low average noise rate of 300 to 500 Hz and a timing resolution of ~3 ns for single photoelectron pulses. With a trigger requiring at least 8 PMT hits, the event rate is ~25 Hz. The challenge is how to sieve out the tiny fraction of these that represent upward-going muons.

The most important results of the '95-'96 season are:

• installation (at various depths) of light sources including a nitrogen laser (λ = 337 nm);

• $\lambda_e \approx 24$ m, independent of wavelength, with an estimated $\langle\cos\theta\rangle \approx 0.8$. This large value of λ_e and its lack of dependence on depth between 1650 and 1850 m confirm the prediction that bubbles are absent at these depths;

• measurements at wavelengths down to 337 nm showing that $\lambda_a \approx 10^2$ m, nearly independent of wavelength between 337 and 450 nm and independent of depth between 1650 and 1850 m;

• installation of an improved supernova/gamma-ray burst trigger;

• installation of two radio receivers by the Bartol/Kansas RICE (Radio Ice Cherenkov Experiment) group.

A subset of ~5 × 10^5 muons that traversed both AMANDA A and B has been collected and is being analyzed. No upward-going muon tracks have yet been seen in these data. The rate of such coincidences is ~0.1 Hz. On a plot of depth *vs* time, the distribution of PMT hits in AMANDA A shows large scatter consistent with scattering by bubbles, whereas in AMANDA B the PMT hits fall on a straight line with slope equal to the velocity of light in ice (see Fig. 11 of the summary talk at this conference by F. Halzen). A study of such plots shows that many of the muons record hits in all four strings, and the scatter is small enough to permit accurate determination of trajectories.

A few candidates for upward-going muons have been recorded in the four-string AMANDA B, but most of the data have only recently been recovered on tapes. In view of the fact that the simulations show that angular resolution, up-down rejection, and effective area are so much better with ten than with four strings, we are concentrating on analyzing data from the ten-string array just completed.

Simulations done by our collaboration have led to a 10-string design for AMANDA B. During the recent 1996-97 season, we drilled six holes to depths of ~1860 m and deployed strings with Hamamatsu PMTs, all downward-facing, at vertical intervals of 10 m. 210 of the 216 PMTs survived refreezing and are operating with typical noise rates ~1500 Hz. With experience in handling the PMTs, the survival rate now exceeds 97%, and the overall mean time between PMT failure is >300 years. The full 10-string AMANDA B, with about 290 working PMTs, is now complete. The drilling was faster and required less power than in previous seasons. New instruments include:

- a 313-nm DC source, a variable DC source tuned by a motorized monochromator, and a new, brighter nitrogen laser, all at depths of ~1850 m;
- 3 working radio receivers and 1 radio transmitter at shallow depths, deployed by the Bartol/Kansas group;
- a transmissometer at a depth of 1800 m to measure attenuation length at 660 nm of ice inside the hole during the refreezing process;
- 18 analog modules with optical fibers for data transmission;
- 2 modules for digital transmission of PMT waveforms.

Data taken with the DC sources are now being analyzed at wavelengths from 313 to 560 nm. Light from the pulsed nitrogen laser is visible up to the tops of the strings. The transmissometer suggests that the attenuation length at 660 nm may be only ~40 cm in the refrozen ice in the hole. Our analysis of water shows that the concentration of Fe, Zn and Al is less than 10 ng/g in all South Pole samples including water pumped through the drill equipment. This suggests that the attenuation is due not to contamination by rust and other impurities but to bubbles of air that existed in air-hydrate crystals prior to melting. We do not know yet whether the bubbles are trapped on the surfaces of the transmissometer or are more uniformly distributed.

Tests of analog data transmission on optical fibers and of digital data transmission are giving encouraging results. Individual nanosecond pulses are resolvable, unbroadened by transmission over 2 km.

5 Optical Properties of South Pole Ice

AMANDA A is located in ice that has an extremely low dust concentration, with $\lambda_a > 250$ m in the blue, but with residual air bubbles giving rise to values of λ_e that increase from ~0.4 to ~1 m at depths from 0.8 to 1 km. AMANDA B at 1.55 to 1.9 km is in bubble-free ice, with $\lambda_e \approx 24$ m, but with a higher concentration of insoluble dust than in AMANDA A. Analysis of data from the nitrogen laser and several other light sources shows that absorption by dust has a wavelength dependence $\lambda^{-0.5}$ to λ^{-1} in the region 337 nm $\leq \lambda \leq$ 450 nm and an absolute value $\lambda_a \approx 10^2$ m at 337 nm. We now have a self-consistent picture of scattering and absorption in terms of Mie theory and of a dust size distribution assumed to be the same as measured many years ago for dust in a solid core taken down to 212 m in South Pole ice. That dust distribution is log normal with a modal diameter 0.1 μm and a width of 2. For an imaginary refractive index typical of minerals, Mie theory predicts that

- scattering is independent of wavelength for $300 < \lambda < 600$ nm;
- absorption goes as $\sim\lambda^{-1}$ in the same interval;
- the absolute concentration is ~100 ng/g for insoluble dust.

From published studies of dust in Vostok solid cores, and scaling from snow accumulation rate at Vostok to that at South Pole, we find a quantitative concurrence with the value ~100 ng/g throughout the depth interval studied at AMANDA B (1600 TO 1830 m). Assuming the same scaling down to bedrock, we have used Vostok dust data to predict λ_a as a function of depth and wavelength in South Pole ice. A comparison of optical properties of ocean, lake, and ice [5] shows that for calorimetry of electron-neutrino interactions, and taking into account PMT quantum efficiency and pressure vessel transparency, ice at depths 1.6 to 1.8 km is somewhat more sensitive than water, and ice at depths below 2.2 km, where dust concentration is much smaller than at 1.6-1.8 km, should be far more sensitive. Furthermore, at depths >2.2 km, scattering is predicted to be a factor 2 to 3 weaker. For tracking muons, the greater transparency of ice at 1.6 to 1.8 km than of water compensates for the shorter scattering length of ice than of water. As discussed in section 6, one can use the earliest arriving photons from a muon track to reconstruct the trajectory and then use all the photons to do calorimetry.

6 Filtering and Track-Fitting of Upward Muon Trajectories

We have developed a fast data-filter that provides a sample enriched in upward muons [6]. These data can be transmitted by satellite and studied throughout the year before the full data on tapes at the South Pole become available.

We now have two nearly independent codes for reconstruction and detector simulation that agree with each other and with early tests of the four-string AMANDA B data. One of them uses a maximum-likelihood fitter for both the 4-string and 10-string AMANDA B data [7]. It simulates optical properties, taking into account the distribution of time delays of scattered relative to unscattered Cherenkov photons. At present only one cut is made: defining N_{direct} to be the number of hits for which $\delta t \equiv t_{hit} - t_{unscatt} \leq 24$ ns, it is required that $N_{direct} > 5$. These photons give the most accurate measure of trajectory. Photons with $\delta t > 24$ ns have undergone substantial scattering but can still be used to infer energy. For the present AMANDA B geometry, with array radius ≈ 60 m, we calculate an effective area of ~10^4 m^2, a median pointing error of ~2.5°, and a downward rejection ratio better than 10^5 (no misreconstructed downward muon in 10^5 trials) [7]. Preliminary results for a future array called AMANDA II (see section 7) are that a pointing error as small as ~1° and an effective area of ~10^5 m^2 can be attained with 10 strings on a circle of radius ~10^2 m instrumented with ~80 PMTs per string at depths from ~1.8 to 2.6 km. The calculated up-down rejection ratio is <1 fake per 10^7 downward-going muons for point sources. The pointing resolution can be checked with coincidences between A and B and between AMANDA and SPASE (South Pole Air Shower Experiment).

7 AMANDA II: toward 1 km^3

The next step toward a 1 km^3 observatory is called AMANDA II. Hardware goals for AMANDA II next season include

- drilling 3 to 4 holes to a depth of 2600 m;
- determination of ice properties over the entire depth interval from 1400 to 2600 m;
- instrumentation of 1-km-long strings (72 or perhaps even 100 optical modules per string, some of which will transmit data on optical fibers); new data acquisition system; new front-end electronics; new calibration techniques; and the first step toward a new method for determining positions of optical modules for the much larger array.

The tentative plan for AMANDA II, predicated on success in deploying at least 3 strings to 2600 m in '97-'98, is to drill and instrument a total of ten 1-km-deep holes on a 100-m radius during the next three years, with the expectation of achieving 1^o pointing and an effective area of up to 10^5 m^2, depending on muon energy.

Detailed planning for the ultimate observatory, of effective volume 1 km^3, will depend upon the outcome of studies of optical properties down to 2.6 km with the first three strings of AMANDA II. The ten-string AMANDA II array will form the core of the km^3 observatory.

Acknowledgments

AMANDA is funded by the Physics and Polar Programs Divisions of NSF, by DESY, by the Wallenberg Foundation (Sweden), and by U. C. Berkeley, U. C. Irvine, and U. Wisconsin.

References

1. L. Nellen, K. Mannheim and P. L. Biermann, Phys. Rev. D **47**, 5270 (1993); F. Halzen, astro-ph/9608185, 28 Aug 1996.
2. D. Eichler, M. Livio, T. Piran, and D. Schramm, Nature **340**, 126 (1989).
3. F. Halzen and G. Jaczko, astro-ph/9602038, 7 Feb 1996; E. Waxman and J. Bahcall, astro-ph/9701231, 29 Jan 1997.
4. P. B. Price, Science **267**, 1802 (1995).
5. P. B. Price, "Implications of optical properties of ocean, lake, and ice for ultrahigh-energy neutrino astrophysics", Applied Optics, in press (1997).
6. John E. Jacobsen, Ph. D. thesis, University of Wisconsin - Madison, 1996.
7. S. Hundertmark, Ch. Wiebusch, and R. Wischnewski, "Optimisation of the Amanda-B detector geometry including a first approach to muon reconstruction", AMANDA note, Zeuthen, Dec., 1996.

† The AMANDA Collaboration now includes:

• University of California at Berkeley: Ryan C. Bay, Yudong He, Douglas M. Lowder, Predrag Miocinovic, David Nygren, P. Buford Price, Austin A. Richards, and Kurt Woschnagg

• University of California at Irvine: Steven W. Barwick, Patrick C. Mock, Rodin Porrata, Eric Schneider, and Gaurang Yodh

• University of Pennsylvania: Douglas Cowen

• University of Wisconsin at Madison: Cesar G. S. Costa, Lori Gray, Francis Halzen, John Jacobsen, Vijaya Kandhadai, Igor Liubarsky, Robert Morse, and Serap Tilav

• Bartol Research Institute: Timothy C. Miller

• Stockholm University, Sweden: Eduardo C. Andrés, Per Askebjer, Lars Bergström, Adam Bouchta, Eva Dalberg, Patrik Ekström, Bengt Erlandsson, Ariel Goobar, Per Olof Hulth, Qin Sun, and Christian Walck

• University of Uppsala, Sweden: Allan Hallgren, Carlos Perez de los Heros, Pawel Marciniewski, and Hector Rubinstein

• Kalmar University, Sweden: Staffan Carius, and Pär Lindah

• DESY (Zeuthen), Germany: Hans Heukenkamp, Stephan Hundertmark, Albrecht Karle, Thomas Mikolajski, Christian Spiering, Ole Streicher, Thorsten Thon, Christopher H. Wiebusch, and Ralf Wischnewski

• Gary Hill and Robert Schwarz (Winter-over scientists)