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Neutrino Telescopes in Antarctica

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Abstract: It is hoped that in the near future neutrino astronomy will reach throughout and beyond our galaxy and make measurements relevant to cosmology, astrophysics, cosmic-ray and particle physics. The construction of a high-energy neutrino telescope requires a huge volume of very transparent, deeply buried material such as ocean water or ice, which acts as the medium for detecting the particles. I will describe two experiments using Antarctic ice as this medium: the AMANDA experiment employing photomultiplier tubes and RICE utilising radio receivers.

Keywords: cosmic rays

1 Introduction

A new window on the universe has been opened with the development of neutrino telescopes. Detection of high energy ($> 10^{12}$ eV) cosmic neutrinos represents a unique opportunity to probe the distant universe. Photons of such high energy are likely to interact with the cosmic microwave background (CMB) and protons, being charged, will have their trajectories bent in galactic and intergalactic magnetic fields. Neutrinos will not interact with CMB photons and will point directly back to their source, giving essential information on these sources.

Arguably the best justification for neutrino telescopes is based on history—the opening of each new astronomical window has led to unanticipated discoveries. Although the most exciting discoveries made by neutrino telescopes may well be unexpected, these multi-purpose scientific instruments have scientific goals from the fields of particle physics, astronomy, cosmology and cosmic ray physics.

Active galactic nuclei (AGN) and gamma-ray bursts (GRB) must be considered as well motivated sources of high energy neutrinos since they are the source of the most energetic photons. The production of neutrinos in AGN and GRB requires the acceleration of hadrons as opposed to purely electron acceleration which is used in many models of AGN. The central engine and the jets associated with blazers have been identified as possible sources of high energy neutrino fluxes within AGN (see e.g. Stecker et al. 1991, 1992; Stecker & Salamon 1996; Szabo & Protheroe 1992, 1994; Protheroe 1997; Mannheim 1993, 1995, and references within). Gaisser, Halzen & Stanev (1995) gave a general discussion of the production of neutrinos in AGN. In their pioneering paper Stecker et al. (1991) integrated theoretical results for generic AGN to estimate the diffuse neutrino flux from all the active galaxies in the universe. One of the goals of neutrino telescopes is to detect this flux. A recent review of the neutrino flux from AGN for several models was given by Protheroe (1998). Neutrino telescopes could distinguish between competing models of the underlying physics using the different energy dependence predicted for the flux. The requirements for a neutrino telescope based on radio receivers to achieve this were discussed by Frichter, Ralston & McKay (1996).

Correlation of ultra-high energy neutrino fluxes at Earth with gamma-ray burst observations would provide essential information on the nature of these extraordinarily luminous sources, much as correlations between neutrinos with photons from SN1987A provided insight into the neutrino sector from supernovae. It has recently been suggested (Waxman & Bahcall 1997) that the highest energy cosmic rays and the highest energy gamma-ray bursts observed at Earth have a common origin—the lack of temporal coincidence can be attributed to the greater pathlength that charged particles travel due to bending in magnetic fields. However, since neutrinos experience no such deflection, they offer the possibility of simultaneous observation with gamma-ray bursts.

The neutrinos referred to so far are produced by cosmic rays *at their acceleration site*. Neutrinos will also be produced when cosmic rays interact with the interstellar medium and the cosmic microwave background.

High energy neutrinos will be produced by cosmic-ray interactions with interstellar gas. This diffuse galactic neutrino background should exist with an intensity comparable to the diffuse galactic gamma-ray background. A survey of predictions was given by Gaisser, Halzen & Stanev (1995) and Protheroe

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(1998). At ultra-high energies, cosmic rays will interact with the photons of the cosmic microwave background radiation resulting in the Greissen–Zatsepin–Kuzmin (GZK) cutoff in the cosmic ray spectrum. Ultra-high energy neutrinos with an energy spectrum peaked around 10^{20} eV will be produced in these interactions. Seckel & Frichter (1999) discussed detection of these neutrinos using a large radio array.

The indirect detection of dark matter is another goal of neutrino telescopes. Cold dark matter particles annihilate into neutrinos with massive cold dark matter particles producing high energy neutrinos which can be detected by high-energy neutrino telescopes. Additionally there is a great deal of particle physics information, in particular related to neutrino oscillation, which can be deduced from, for example, the angular distribution of upward-coming neutrino events.

2 Neutrino Telescopes in Antarctica

A neutrino telescope detects the Cherenkov radiation generated in water or ice by the passage of relativistic charged particles produced by neutrino collisions with nucleons in the detector volume. The weakness of the neutrino interaction means that a large volume of material is required in the detector. The Antarctic ice-cap is the largest homogeneous mass of high-purity material on Earth (Askebjer et al. 1995). This makes the South Pole a very attractive location for neutrino detection. Furthermore, the deployment of the detector array in ice through hot water drilling has proved more successful than attempts to deploy detectors in ocean water. The South Pole is home to two high energy neutrino telescopes—AMANDA (Antarctic Muon And Neutrino Detector Array) and RICE (Radio Ice Cherenkov Experiment).

3 AMANDA

AMANDA uses photomultiplier tubes to detect the optical Cherenkov cones which result from muons produced in muon neutrino charged current interactions. Its architecture is optimised for reconstructing upgoing neutrino-induced muons of typical energy 10^{11}–10^{15} eV. By looking for upgoing muons it is possible to control the background associated with the muons produced by cosmic-ray interactions in the Earth's atmosphere. AMANDA is sensitive to atmospheric neutrinos produced in the northern hemisphere atmosphere of the Earth as well as the higher energy neutrinos discussed in the Introduction. In comparison, the Japanese Super Kamiokande neutrino detector is limited by its size to detecting neutrinos with energies below 10^{10} eV.

During the 1993–94 austral summer, four strings were deployed with photomultiplier modules at depths of 800 to 1000 m. However, residual bubbles in the ice scattered the Cherenkov photons preventing a proper reconstruction of the muon path. A deeper array, AMANDA-B has been deployed in bubble-free ice below 1500 m (at a depth of ~1300 m the last air bubbles have transformed into air hydrate crystals). There is still some scattering due to dust in the ice, however this is isolated to several well-defined depths (Woschnagg 1999) and the current array has enabled the reconstruction of muon paths. A coincidence trigger with the South Pole Air Shower Experiment is being used to calibrate pointing accuracy and ice properties (Miller 1999). AMANDA-B consists of ten strings with 300 optical modules each consisting of a photomultiplier tube, presenting an effective area for muon tracking of the order of 10^4 m^2 (Hill 1999).

Analysis of 113 days of AMANDA-B data from April to November 1997 has yielded 16 neutrino candidate events. These 16 candidates were extracted from around 10^8 events. About 90% of the cosmic ray muons are rejected with a simple filter method using the correlation of arrival times and depth of the observed Cherenkov photons. The remaining data are reconstructed by fitting the Cherenkov light cone generated by a relativistic particle to the observed arrival times. A set of quality cuts is used to further reduce the data. These cuts are based on the number of direct hits, the length of path that the hits are distributed over (at least 100 m), and require that the event was not concentrated at the top or bottom of the detector. The characteristics of the observed neutrino candidates are in agreement with atmospheric neutrino Monte Carlo simulations (Karle 1999). A full simulation of atmospheric neutrinos predicts that 21 events pass the cuts described.

The most optimistic predictions for the diffuse neutrino flux predict an event rate of a few per year for AMANDA-B with other intensity estimates being marginal. During the 1997–98 season construction of AMANDA-II was begun, which will have an effective area several times larger than AMANDA-B. Three strings were deployed with optical modules ranging from 1300 to 2400 m. These will be used to investigate the optical properties of polar ice over this depth range and will constitute the first three strings of the new detector. The geometry is shown in Figure 1. Planning is underway to instrument a cubic volume of ice—the IceCube Observatory. The AMANDA collaboration anticipates of the order of 10 neutrinos per year will be detected from sources such as AGN and GRBs with a km^2 telescope (Halzen 1999).

The most promising area for the current AMANDA instrument is transient neutrino sources. The current array has a pointing accuracy of 2·5 degrees per muon track (Hill 1999). The Burst and Transient Source Experiment (BATSE) onboard the Compton

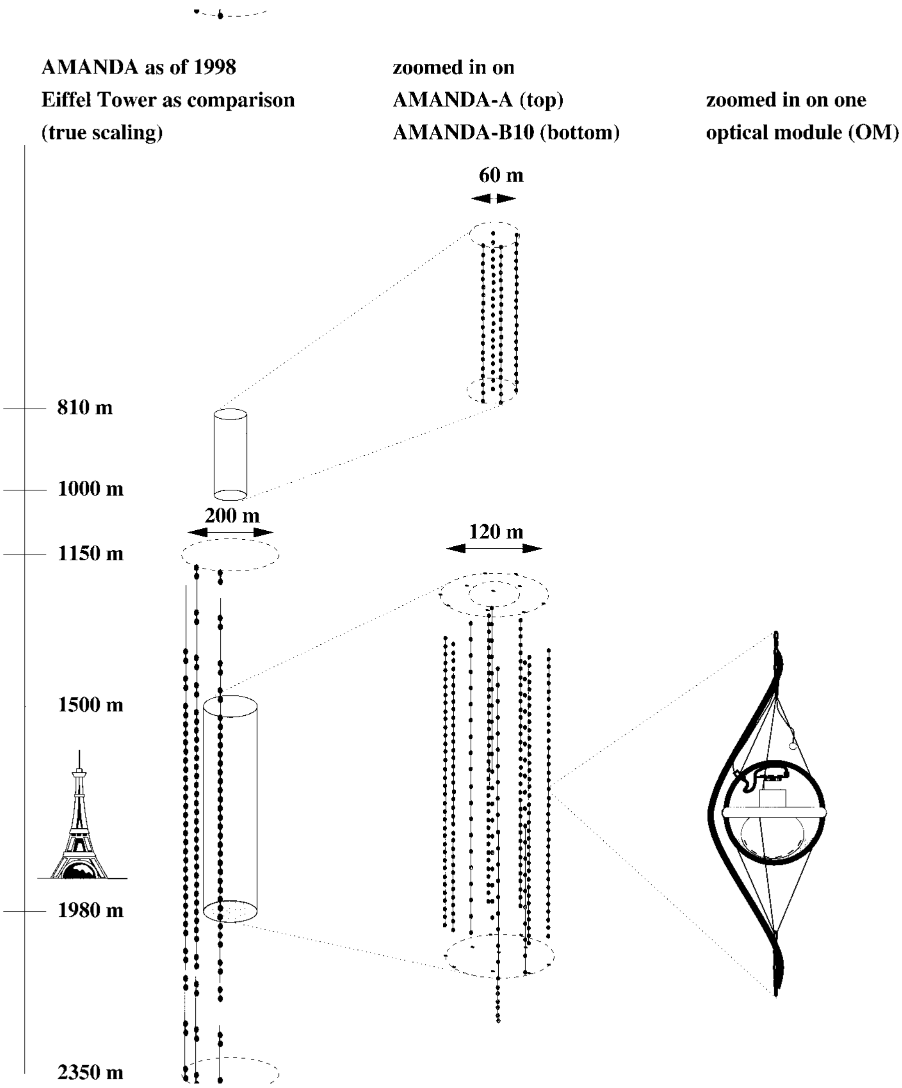

Figure 1—Schematic view of AMANDA-A, AMANDA-B and the three new strings. (Courtesy of Alexander Biron and Thorsten Schmidt of DESY.)

Gamma Ray Observatory provides position and time for GRBs which means that several of the quality criteria cuts can be relaxed. The procedure used to search the data is reviewed by Bay (1999) and Kim (1999).

4 RICE

RICE is optimised to detect the radio-frequency Cherenkov radiation produced when an ultra-high energy ($> 10^{15}$ eV) electron neutrino undergoes a charged current interaction in the ice (see Figure 2). Thus RICE complements AMANDA by extending into the electron neutrino sector and offering a detection strategy for ultra-high energies. For a 10^{15} eV neutrino induced cascade the effective volume offered by one radio receiver in the ice is comparable to one phototube. The ratio of the effective volume of a radio receiver compared with a phototube grows with energy such that a radio receiver offers an effective volume ten times larger than a phototube for 10^{18} eV neutrinos (Price 1996). However, in many astrophysical sources the neutrino energy spectrum falls steeply at high energies. To compare the event rates per year requires knowledge of this neutrino energy spectrum. For example, Price (1996) considered the AGN spectra of Stecker & Salamon (1996) (SS) and Szabo & Protheroe (1994) (SP). Considering single elements in a radio or optical array he found using the SS spectrum that a radio receiver would yield an event rate three times higher than a phototube. However, using the most optimistic of the SP spectrum gave comparable event rates and the least optimistic SP spectrum yielded an event rate a factor of ten lower for radio receivers.

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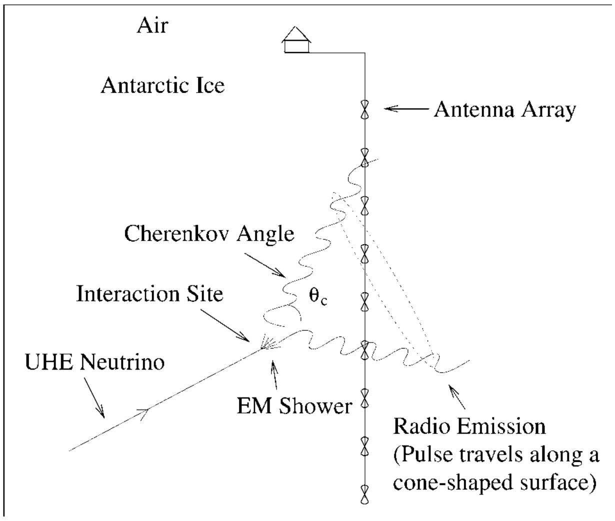

Figure 2—The RICE concept. An ultra-high energy electron neutrino initiates an electromagnetic shower in the Antarctic ice. The resulting radio pulse is detected by a buried array of radio receivers.

Above 10^{15} eV electron neutrinos will be readily absorbed by charged-current interactions in the Earth. Thus, in contrast to AMANDA, RICE searches for downgoing neutrinos. Since atmospheric muons do not trigger RICE it is not necessary to use the Earth as a shield as AMANDA does.

An ultra-high energy ν_e that undergoes a charged-current interaction in the ice will transfer most of its energy to the resulting electron and subsequent electromagnetic shower. A charge imbalance will develop as positrons are annihilated and atomic electrons are scattered into the shower. Monte Carlo calculations show that the net charge is about 20% of the total number of electrons (Zas, Halzen & Stanev 1992). The moving blob of net negative charge will produce coherent Cherenkov radiation at wavelengths larger than its own spatial extent ($\sim$ 10 cm), corresponding to radio frequencies ($\nu \leq 1$ GHz). The detection geometry is displayed in Figure 2, showing the Cherenkov cone produced by an electromagnetic shower being detected by suitably located radio receivers.

RICE currently consists of a 16 channel radio receiver array in the ice. In the 1995–96 austral summer the AMANDA collaboration graciously consented to allow cables and radio antenna modules to be dropped in two AMANDA holes. Two antennas plus associated receiver electronics were deployed at depths of approximately 250 and 140 m. The objective of this pilot experiment was to demonstrate that a radio-based effort could be launched with minimum impact on AMANDA, and to establish the procedure which would be used for full deployment. In 1996–97 additional hardware was deployed. This consisted of seven dipole antennas, tuned to $\sim$275 MHz with 10% bandwidth. Four of the antennas were deployed as receivers and three as transmitters. Again these were deployed in AMANDA holes. In 1998–99 four dedicated RICE holes were dug using a standard mechanical hole-borer and seven receivers are located in these holes at depths of 120 and 170 m. Three surface horn antennas were also deployed in 1998–99 which are used as a veto of surface-generated noise.

Much of the analysis to date has been concerned with measuring and understanding the noise. A frequency-dependent effective noise temperature has been measured and is filtered at low frequencies. Long duration continuous broadcast backgrounds are also easily filtered. Short duration 'burst' noise backgrounds from the surface or AMANDA below have been the subject of recent investigation and elimination based on the timing sequence of hits on various receivers is proving successful.

Since 30 January 1999 RICE has accumulated $\sim$45 days of livetime. The overwhelming majority of the recorded triggers to date are consistent with surface-generated noise backgrounds; no clear neutrino candidates have been observed. Analysis is currently in progress; roughly, every 15 days of livetime corresponds to a sensitivity level comparable to 1% that of the Stecker and Salamon (1996) predictions for the incident ultra-high energy neutrino flux. This is based on Monte Carlo simulations of the current relatively small array. The RICE Monte Carlo simulations were described by Frichter, Ralston & McKay (1996). Monte Carlo investigation of an extended 25 element RICE array indicates that an energy resolution of $\sim$20% and an angular resolution of $<$1–5° is achievable, depending on the signal geometry.

A recent review of the status of RICE with a detailed account of event characteristics and reconstruction is given by Frichter (1999). A full list of personnel is also included in this review.

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References

Askebjer, P., et al. 1995, Science, 267, 1147
Bay, R. 1999, in ICRC XXVI: Proc. 26th Int. Cosmic Rays Conf., ed. D. Kieda et al., Vol. 2, 225 Section HE 4·2·06
Frichter, G. M. 1999, in ICRC XXVI: Proc. 26th Int. Cosmic Rays Conf., ed. D. Kieda et al., Vol. 2, 467 Section HE 6·3·12
Frichter, G. M., Ralston, J. P., & McKay, D. W. 1996, Phys. Rev. D, 53, 1684
Gaisser, T. K., Halzen, F., & Stanev, T. 1995, Phys. Rep., 258, 173

Halzen, F. 1999, in ICRC XXVI: Proc. 26th Int. Cosmic Rays Conf., ed. D. Kieda et al., Vol. 2, 428 Section HE 6·3·01
Hill, G. C. 1999, in ICRC XXVI: Proc. 26th Int. Cosmic Rays Conf., ed. D. Kieda et al., Vol. 2, 432 Section HE 6·3·02
Karle, A. 1999, in ICRC XXVI: Proc. 26th Int. Cosmic Rays Conf., ed. D. Kieda et al., Vol. 2, 221 Section HE 4·2·05
Kim, J. H. 1999, in ICRC XXVI: Proc. 26th Int. Cosmic Rays Conf., ed. D. Kieda et al., Vol. 2, 196 Section HE 4·1·14
Mannheim, K. 1993, A&A, 269, 67
Mannheim, K. 1995, Astropart. Phys., 3, 295
Miller, T. C. 1999, in ICRC XXVI: Proc. 26th Int. Cosmic Rays Conf., ed. D. Kieda et al., Vol. 2, 465 Section HE 6·3·11
Price, P. B. 1996, Astropart. Phys., 5, 43
Protheroe, R. J. 1997, in Accretion Phenomena and Related Outflows, ed. D. T. Wickramisinghe et al., ASP Conf. Series, Vol. 121 (San Francisco: ASP), p. 585 (astro-ph/960““)
Protheroe, R. J. 1998, astro-ph/9809144
Seckel, D., & Frichter, G. 1999, in ICRC XXVI: Proc. 26th Int. Cosmic Rays Conf., ed. D. Kieda et al., Vol. 2, 471 Section HE 6·3·13
Stecker, F. W., & Salamon, M. H. 1996, Space Sci. Rev., 75, 341 (astro-ph/9501064)
Stecker, F. W., Done, C., Salamon, M. H., & Sommers, P. 1991, Phys. Rev. Lett., 66, 2697
Stecker, F. W., Done, C., Salamon, M. H., & Sommers, P. 1992, Phys. Rev. Lett., 69, 2738(E)
Szabo, A. P., & Protheroe, R. J. 1992, Phys. Rev. Lett., 69, 2285
Szabo, A. P., & Protheroe, R. J. 1994, Astropart. Phys., 2, 375
Waxman, E., & Bahcall, J. 1997, Phys. Rev. Lett., 78, 2292
Woschnagg, K. 1999, in ICRC XXVI: Proc. 26th Int. Cosmic Rays Conf., ed. D. Kieda et al., Vol. 2, 200 Section HE 4·1·15
Zas, E., Halzen, F., & Stanev, T. 1992, Phys. Rev. D, 45, 362

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