High-energy neutrinos

Eli Waxman[1] and Karl Mannheim[2]
[1] Weizmann Institute of Science, Rehovot, Israel
[2] University of Würzburg, Germany

Several neutrino "telescopes" allow today the detection of Solar Mega electron-Volt (MeV) neutrinos, thus enabling direct observations of nuclear reactions in the core of the Sun, which is opaque to photons, as well as studies of fundamental neutrino properties. These telescopes are also capable of detecting MeV neutrinos from supernova explosions in our local Galactic neighborhood, such as the well-known supernova 1987A, at distances $<10^5$ light years. The construction of high energy, Tera electron-Volt (TeV), neutrino telescopes is aimed at extending the distance accessible to neutrino astronomy by some five orders of magnitude, to the edge of the observable Universe, and at opening a new window of observations at high neutrino energy.

an unexplored window of observations is about to be opened, one should be ready for surprises

A kilometer-squared effective area telescope is required to detect estimated neutrino signals. The feasibility of the construction of such large volume detectors in deep water or ice has been demonstrated by the Baikal and AMANDA experiments, and several projects are now under way for the construction of kilometer scale telescopes. Although the expected event rates are small, even a handful of events will have profound implications for both high-energy astrophysics and particle physics. Moreover, as an unexplored window of observations is about to be opened, one should be ready for surprises.

From the Sun to the edge of the Universe: The need for kilometer scale telescopes

Due to the small cross section of neutrino interactions, kilo-tons of detector material are required to observe MeV neutrinos produced in the core of the nearby Sun. The detection of such neutrinos from cosmologically distant sources is impossible using present techniques. This situation changes at higher neutrino energy, due to two reasons. First, the cross section of the interaction increases with energy. Second, at TeV neutrino energy the construction of giga-ton, rather than kilo-ton, telescopes becomes feasible.

Interactions of high energy, >1 TeV, muon neutrinos with nucleons produce muons, which propagate over more than a kilometer through rock, water or ice. The muon track, a straight line co-linear to within one degree with the initial neutrino trajectory, may be identified by an array of photo-multipliers detecting the muon Cerenkov emission of visible light. The DUMAND experiment off the coast of Hawaii demonstrated the feasibility of detection of high energy muons in deep sea water, and the Lake Baikal experiment was the first to detect high energy neutrino induced muons. The AMANDA collaboration has demonstrated that deep ice is also a suitable medium, and that construction of kilometer-scale detectors is feasible, by the construction at the South Pole of the first neutrino telescope with 10^4 m^2 effective area at 1 TeV. Fig. 1 shows a neutrino event detected by the AMANDA telescope.

Nuclear fusion in stars generally ceases to be important at TeV energy. At this high energy, different types of sources are expected to show up. Guidance to estimating the expected neutrino signal is provided by cosmic-ray and gamma-ray observations. The cosmic-ray spectrum extends to energies $\sim 10^{20}$ eV, and is likely dominated beyond 10^{19} eV by extra-Galactic protons. Whatever the sources are, some fraction of the protons are expected to produce pions as they escape their source by either hadronic collisions with ambient gas or photoproduction with source photons, leading to electron and muon neutrino production through the decay of charged pions. Waxman & Bahcall have shown that cosmic-ray observations set an upper bound to the neutrino flux from sources which, like candidate sources of $>10^{19}$ eV protons, are optically thin for high energy nucleons to γp and p-p(n) interactions. This upper bound is compared in Fig. 2 with the flux sensitivity of neutrino telescopes, demonstrating the need for a kilometer-scale telescope.

Sources may exist, where pion production losses prevent the escape of high-energy nucleons and allows only neutrinos (and

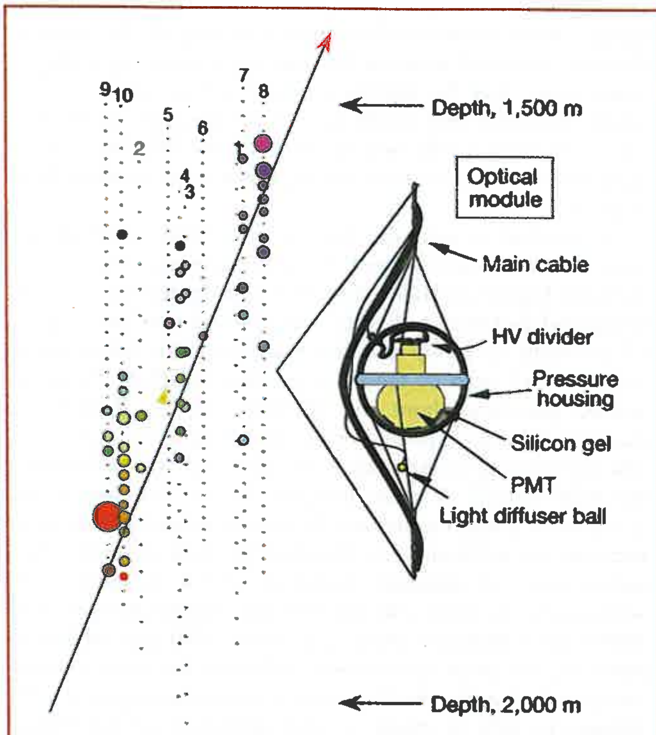

Fig. 1: The arrow indicates the track of a high energy neutrino induced muon passing through the AMANDA detector [E. Andres *et al.*, Nature **410**, 441 (2001)]. The detector is composed of strings of optical modules, represented by dots and shown in detail on the right, deployed 2 km deep under the South-Pole surface. The muon is identified through the detection by photo-multipliers (PMTs) of its Cerenkov emission of visible light. Colored circles show PMT pulses: The size of the circle indicates the pulse amplitude, and its color corresponds to photons' arrival time (earlier times are red and later times are blue). The large background of down moving cosmic-ray muons is rejected by looking for only up moving muons, produced by neutrinos which have crossed the Earth. Above 10^3 TeV, where the Earth becomes opaque to muon neutrinos, a cubic-kilometer Cerenkov telescope may discriminate horizontal and down going neutrino events from the low-energy background by identifying their high energy.

Article available at http://www.europhysicsnews.org or http://dx.doi.org/10.1051/epn:2001605

possibly low energy gamma-rays) to escape. While cosmic-ray data do not constrain the possible neutrino flux from such sources, which may therefore exceed the bound shown in Fig. 2, it also does not provide evidence for the existence of such "hidden" sources.

The ANTARES and NESTOR collaborations plan to construct during the next few years 0.1 km^2 detectors in the Mediterranean Sea. The long-term goal of high-energy neutrino astronomy is the construction of 1 km^2 (or cubic-kilometer, after multiplication with the muon range) telescopes. The AMANDA collaboration is planning ICECUBE, a square-kilometer extension of the South-Pole detector, and the NEMO collaboration carries a site study for a square-kilometer Cerenkov telescope in the Mediterranean. Above 10^3 TeV, neutrino detection may be possible also using other techniques, based on horizontal neutrino-induced air showers, radio observations of the moon's limb, and acoustic or radio detection of horizontal events in deep water or ice.

Astrophysics with kilometer scale telescopes

The sources of $>10^{19}$ eV cosmic rays are yet unknown. Gamma-ray bursts (GRBs) and TeV-photon emitting active galactic nuclei (AGN) have been suggested as possible sources. GRBs are transient sources lying at cosmological distances, producing short (typically 1 to 100 s long) flashes of γ-rays with apparent luminosities exceeding that of the sun by 18 orders of magnitude. They are believed to be powered by the accretion of a fraction of a solar mass on second time scale onto a newly born solar mass black hole. AGN are steady sources, with luminosities of the order of 10^{12} Solar, believed to be powered by accretion of mass onto massive, million to billion solar masses, black holes residing at the centers of distant galaxies. Few tens of ~100 TeV events per year, correlated in time and direction with GRBs, are expected in a kilometer-squared telescope if GRBs are the sources of ultra-high energy protons. A lower rate is expected if TeV-photon emitting AGN are producing the ultra-high energy protons.

In both GRBs and AGN, mass accretion is believed to drive a relativistic plasma outflow, which results in the emission of high-energy radiation. A similar process is believed to power Galactic Micro-Quasars, which may be considered as a scaled down version of AGN, with ~1 Solar mass black hole (or neutron star) "engines". In all cases, neutrino observations may provide unique information on the physics of the underlying engine, which is not well understood despite many years of photon observations. In particular, the answer to the question of whether or not the outflowing plasma carries baryons, which has major implications to the energy extraction mechanism, is not yet known. A positive answer implies, for example, that a kilometer-squared telescope may detect tens of events per year associated with Micro-Quasars.

A neutrino beam over cosmological baseline

The production of tau neutrinos, through charmed meson production, is expected to be negligible in astrophysical sources. However, atmospheric neutrino observations suggest muon to tau neutrino oscillations with strong mixing. Thus, a high-energy neutrino telescope would be an "appearance experiment" where equal numbers of ν_μ's and ν_τ's are detected, as long as the neutrino mass difference squared exceeds 10^{-16} eV^2.

A neutrino telescope will operate in coincidence with space and ground based high-energy photon telescopes. This may be particularly valuable for GRB observations. Looking for a neutrino signal in a given time and direction, set by γ-ray observations, implies a background free observation. Moreover, the simultaneity of neutrino and photon arrival times may be tested to ~1 s accuracy. For propagation over cosmological scales this implies checking the assumption of special relativity, that photons and neutrinos have the same limiting speed, to 10^{-16} fractional accuracy, and the weak equivalence principle, according to which photons and neutrinos should suffer the same time delay as they pass through a gravitational potential, to 10^{-6} fractional accuracy. This is many orders of magnitude better than present upper limits (of order 10^{-8} and 10^{-2} respectively).

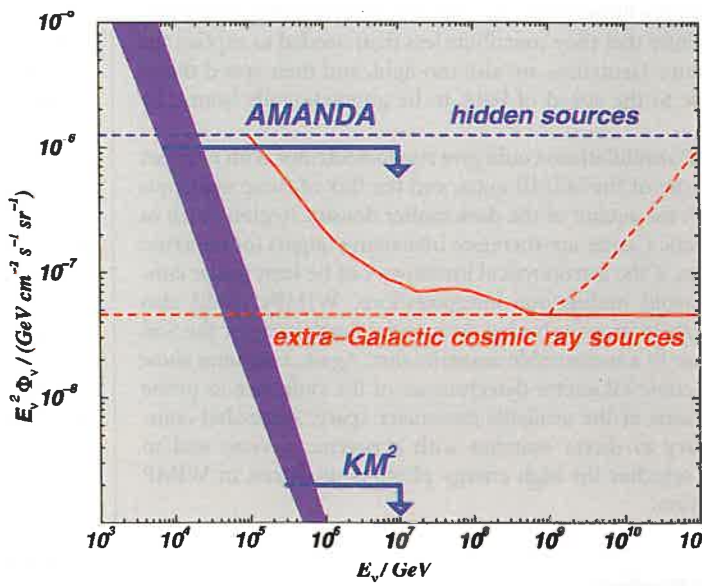

Fig. 2: The experimental upper bound on neutrino intensity established by the AMANDA detector [E. Andres *et al.*, Nucl. Phys. B (Proc. Suppl.), **91**, 423 (2001)], compared to the sensitivity achievable by a 1 km2 detector. The atmospheric neutrino background is shown as a blue strip indicating its variation from vertical to horizontal directions. The sensitivity of the detectors to variable point sources is greater than shown, since the background is much reduced for a search in given time and direction windows.
The solid red curve shows the upper bound imposed by cosmic-ray observations on the intensity of **muon** neutrinos [E. Waxman & J. N. Bahcall, Phys. Rev. **D59**, 023002 (1999); K. Mannheim, R. J. Protheore & J. P. Rachen Phys. Rev. **D63**, 023003 (2001); J. N. Bahcall & E. Waxman, Phys. Rev. **D64**, 023002 (2001)]. The dashed line extension to lower energies is the bound obtained under the assumption that the extra-Galactic proton energy generation rate below 10^{17} eV, which is uncertain due to Galactic cosmic-ray background, does not exceed the generation rate derived from observations at higher energy. The dashed line extension to high energies is obtained under the assumption that the extra-Galactic proton energy generation rate increases rapidly beyond 10^{20} eV, where the cosmic-ray flux is not well constrained by observations. The dashed blue line indicates the maximum intensity allowed for putative extragalactic nucleon accelerators, the existence of which is "hidden" from cosmic-ray detectors due to energy loss which prevents nucleon escape.

Neutrinos and dark matter

Missing mass in the Universe poses a problem for astronomy since Fritz Zwicky's 1933 observations of the velocity dispersion in a cluster of galaxies. There remain sources of gravity unseen at any wavelength despite numerous attempts. This dark matter (and, more recently, also smoothly distributed dark energy) lacks an explanation, but its existence appears naturally in the context of Big Bang cosmology. Approximately 12 billion years ago, the Universe was hot and compact creating particles in pairs at temperatures far above currently available accelerator energies. Supersymmetric extensions of the Standard model indicate that weakly interacting particles created at the electroweak-symmetry breaking scale, i.e. at TeV energies, could have survived until the present day with a matter density of the right order of magnitude, if they carry a conserved new quantum number (the R-parity). The naturalness of producing the correct density makes these weakly interacting massive particles (WIMPs) the currently most favored candidates for non-baryonic dark matter. With the mounting evidence for neutrino mass, one might think of neutrinos as the non-baryonic dark matter. However, given current upper limits on the neutrinos masses and mass splittings, one can infer that they contribute less than needed to explain the dark matter. Neutrinos are also too light, and their speed therefore close to the speed of light, to be gravitationally bound by galaxies.

WIMP annihilations could give rise to neutrinos with energies of the order of the WIMP mass, and the flux of these neutrinos goes with the square of the dark matter density. Regions such as the Galactic Center are therefore interesting targets for neutrino telescopes, if the astrophysical inventory can be kept under control to avoid ambiguous interpretations. WIMPs could also accumulate in massive bodies such as the Earth itself, or the Sun giving rise to a measurable neutrino flux. Again, estimates show that the cubic kilometer detectors are of the right size to probe large regions of the available parameter space, somewhat complementary to direct searches with cryogenic devices and to indirect searches for high energy photons produced in WIMP annihilation.

Further Reading:

[1] Bahcall, J. N., Astrophysical Neutrinos: 20th Century and Beyond, Nuclear Phys. B (Proc. Suppl.), 91, 9-17 (2000)

[2] Gaisser, T. K., Halzen, F. & Stanev, T., *Particle physics with high-energy neutrinos*, Phys. Rep. 258, 173-236 (1995)

[3] Nagano, M., Watson, A. A., *Observations and implications of the ultrahigh-energy cosmic rays*, Rev. Mod. Phys. 72, 689 (2000)

[4] Waxman, E., *High-energy neutrinos from astrophysical sources*, Nucl. Phys. B (Proc. Suppl.), 100, 314 (2001)

[5] Learned, J. G. & Mannheim, K., *High-energy neutrino astrophysics.*, Ann. Rev. Nucl. Sci. 50, 679-749 (2000)

About the authors

Eli Waxman is currently an Associate Professor at the Weizmann Institute of Science (Rehovot, Israel). He has received numerous awards, including the E.D. Bergmann Memorial Award.

Karl Mannheim is professor for astronomy at the University of Würzburg and works mainly in the field of high-energy astrophysics. He was born in Heidelberg in 1963 and studied physics and astronomy in Heidelberg and Bonn, where he received his doctoral degree with a thesis on radio galaxies in 1992.