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Neutrino astronomy: Present and future

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Abstract. I briefly review the present and future status of the burgeoning field of neutrino astronomy. I outline the astrophysics and particle physics goals, design, and performance of the various current and proposed neutrino telescopes. Also described are present results and future expectations.

Keywords. Particle astrophysics; neutrino telescope.

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1. Introduction

The study of high energy astrophysical neutrinos is currently undergoing a very active and exciting period. Current experiments have probed potential astrophysical sources of neutrinos as well as fundamental particle physics. Extensions of present experiments and construction of new detectors are ongoing, which should in the near future build upon previous results. This brief review will focus on such experimental efforts, specifically those conducted with neutrino telescopes. This method, pioneered by DUMAND [1,2], is based on the detection of Cherenkov light from particles produced in neutrino interactions using an array of photomultiplier tubes deployed in water or ice. It is alas beyond the scope of this work to properly cover novel radio and acoustic techniques utilized by, for example, experiments such as GLUE, RICE, ANITA and SAUND [3,4].

After describing the astrophysics and particle physics interests of neutrino astronomy and outlining the general detection principles, I will briefly describe present and future experimental efforts and results.

2. Physics motivation

Neutrinos are expected to be produced in various extreme astrophysical environments such as active galactic nuclei, supernova remnants, and gamma ray bursts. Neutrinos only interact weakly, and this property that makes their detection rather difficult also allows them to point back to their source. This is an advantage over photons, nucleons or nuclei which may interact before detection, either attenuating or absorbing the potential signal. The trajectories of charged particles are also bent in magnetic fields, potentially obscuring any directional information.

Consider a generic source of cosmic rays, one where protons are accelerated via the Fermi mechanism in a region of high magnetic field. These accelerated protons produce neutrinos via photopion production $p\gamma \rightarrow \Delta^+ \rightarrow \pi^+ n$ (including antiparticles) or through inelastic proton–proton scattering. With an expected $\nu_e : \nu_\mu : \nu_\tau$ flavor ratio of $1:2:0$ at the source from the subsequent pion decay: $\pi^+ \rightarrow \mu^+\nu_\mu \rightarrow e^+\nu_\mu\nu_e\overline{\nu}_\mu$, the current most-favored neutrino oscillation scenario will yield a $1:1:1$ flavor ratio at the point of detection. The flux from a generic transparent cosmic ray source is known as the Waxman–Bahcall flux [5] and is $E^2\Phi_{\mathrm{WB}} \sim 10^{-8}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ GeV (where the assumed energy spectrum is E^{-2}). Cosmic rays of energies $\geq 10^{19.5}$ eV have been observed, and if these cosmic rays are protons, then they rapidly lose energy during propagation due to photopion production interactions with the ubiquitous cosmic microwave background photons. The subsequent neutrinos produced can be considered a guaranteed source of high-energy neutrinos.

From the perspective of particle physics, astrophysical neutrinos can prove to be useful tools. High-energy neutrinos can provide probes of electroweak and strong physics in energy ranges and kinematic regions beyond that obtainable in conventional, man-made accelerators. These can include studies of possible deviations from standard neutrino oscillatory behavior, probes of low-x parton distributions in QCD, and searches for new neutrino interactions beyond the Standard Model. Searches for the exotic, such as magnetic monopoles and dark matter, are also possible. For a recent review of the particle physics potential, see for example [6].

It is the search for dark matter that I will pause to describe further. In the minimal supersymmetric model (MSSM) the neutralino is the lightest stable particle and as such is considered a prime dark matter candidate. In the nomenclature of dark matter it is known as a weakly-interacting massive particle: a WIMP. Searches for such WIMPs using neutrino telescopes look for excesses of neutrino fluxes from the center of massive bodies such as the Earth and the Sun. WIMPs should scatter weakly on normal matter and lose energy, eventually getting trapped in the gravitational field of the core. Trapped neutralinos can annihilate pairwise, producing a measurable flux of neutrinos. Searches for such a flux have been conducted and the results are described in §4.

3. Detection principles: Neutrino telescopes

The size of a neutrino telescope is driven by requirements of energy threshold, expected flux, and of course economics. For a flux of neutrinos/GeV/cm^2/s given by $\mathrm{d}F/\mathrm{d}E_\nu$, the number of neutrinos N at time T is given by

$$N = T\int_{E_\nu^{\mathrm{th}}} A(E_\nu)P(E_\nu)\frac{\mathrm{d}F}{\mathrm{d}E_\nu}\mathrm{d}E_\nu, \tag{1}$$

where E_ν^{th} is the energy threshold, $A(E_\nu)$ is the effective detector area, and $P(E_\nu)$ is the probability of detection with the detector volume. Detection of neutrinos

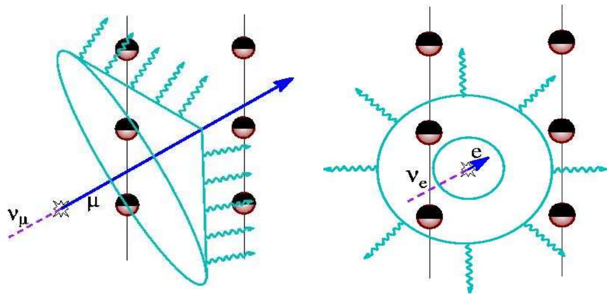

Figure 1. Left: Schematic of ν_μ-induced muon track in detector. Right: Schematic of ν_e cascade.

associated with the highest energy cosmic rays requires a detector with a cubic kilometer volume.

Particles are detected via two interaction channels: tracks and cascades. Tracks come from muons produced in ν_μ charged-current interactions as well as by cosmic ray (atmospheric) muons. Cascades are produced by all flavor neutral-current interactions as well as by ν_e and ν_τ charged-current interactions. Schematics of these channel signals can be seen in figure 1.

The characteristics of each of these channels allow for flavor determination. $\nu_\mu \to \mu$ produces long muon tracks detectable with good angular resolution (typically about a degree), but with typically poor energy resolution. $\nu_e \to e$ produces electromagnetic showers and all flavors produce hadronic showers detectable with good energy resolution but poor directional resolution.

ν_τ interactions can allow for interesting topologies in the detector. With a decay length $l_\tau \sim 50$ m $\times (E_\tau/10^6$ GeV), for energies below 10^6 GeV the shower produced cannot be distinguished from the hadronic shower of the initial interaction. However, above this energy the range of the tau can be a few hundred meters, allowing for a distinctive 'double bang' topology, one where the first bang is the cascade produced by the initial ν_τ interaction and the second is produced by the tau decay. For energies between 10^7–$10^{7.5}$ GeV the decay length becomes comparable to a kilometer and a so-called 'lollipop' topology is possible: a track ending in a cascade.

The dominant background for extra-terrestrial neutrino detection is the flux of downward-penetrating atmospheric muons. To a large extent this background can be eliminated by simply looking only at upwardly-propagating signals; only a neutrino could pass through the earth and interact in or near the detector volume. In this case the background is then the atmospheric neutrino flux, with an energy spectrum $\sim E^{-3.7}$. With the expected neutrino signal energy spectrum $\sim E^{-2}$ appropriate energy cuts can isolate the signal.

4. Experimental efforts and results

4.1 *Baikal*

The Baikal detector, located in Lake Baikal in Siberia, was the first working neutrino telescope. Its initial incarnation, dubbed NT-200, has been in operation since 1998.

This detector is composed of 8 strings, each 72 meters long, with a total of 192 optical modules. An expanded detector, comprised of NT-200 and 3 additional strings, called NT-200+ has been in operation since April 2005. This addition quadruples the effective volume of the detector for cascade detection to 10 Mton. The geometry of the Baikal instrument can be seen in figure 2.

A recent Baikal analysis searched for a diffuse flux of high energy (>10 TeV) neutrinos in the cascade channel using NT-200 [7]. No events were found over the expected background and therefore upper limits on the diffuse flux can be calculated. For an expected E^{-2} spectrum and $1:1:1$ flavor ratio, the upper limit obtained is $E^2\Phi < 8.1\times10^{-7}$ cm^{-2} s^{-1} sr^{-1} GeV over an energy range of 22 TeV to 50 PeV. An additional upper limit on the diffuse $\overline{\nu}_e$ flux at the W resonance energy (6.3 PeV) is found to be $\Phi_{\overline{\nu}_e} < 3.3\times10^{-20}$cm^{-2} s^{-1} sr^{-1} GeV^{-1}. Searching for an excess flux of muon neutrinos from the center of the Earth due to annihilation of neutralinos, Baikal found a flux consistent with the expected atmospheric flux [8]. From this result, a 90% C.L. muon flux limit was derived as a function of possible WIMP mass, competitive with those derived from other experiments.

To further extend the reach of NT-200+, research and development has begun towards a Gigaton Volume Detector (GVD) in Lake Baikal. Such a detector would be composed of subdetectors similar to the NT-200+ design.

4.2 *AMANDA*

The full AMANDA detector, located in the ice at the South Pole, was constructed in stages. The AMANDA-B10 detector has been operating since 1997 and consists of 302 optical modules on 10 strings. Operating since 2000, the AMANDA-II detector builds on AMANDA-B10 and additional strings; the total detector is 19 strings with a total of 677 optical modules. Utilizing various possible detection channels AMANDA has searched for an excess flux of neutrinos beyond the expected background of atmospheric neutrinos.

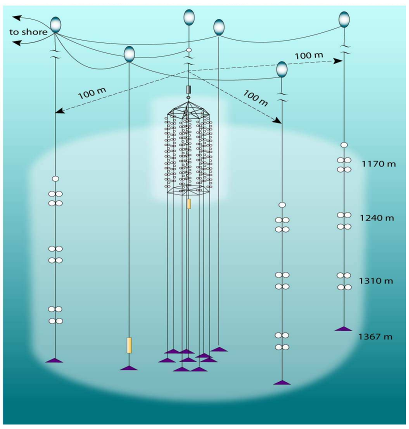

Figure 2. Geometry of the NT-200+ detector at Lake Baikal.

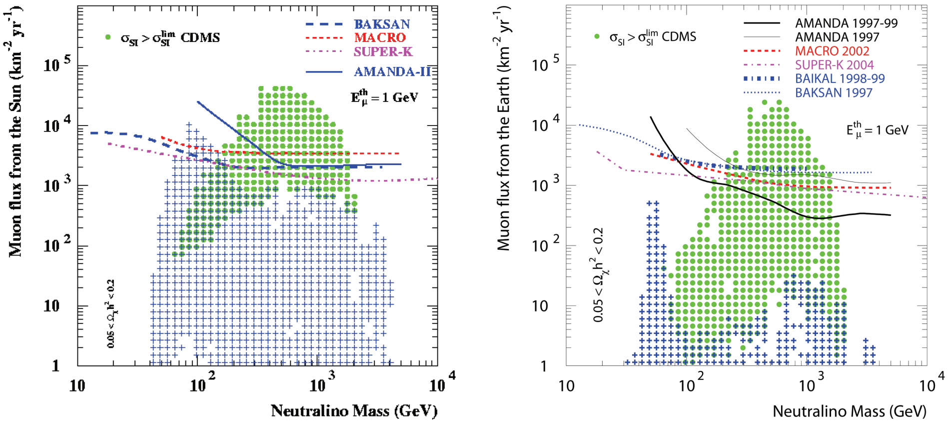

Figure 3. Muon flux limits as a function of neutralino mass from a search for an excess flux from the center of the Sun (left) and the Earth (right). References to other limits can be found in [13].

The AMANDA collaboration searched for ν_μ-induced tracks in the energy range 13 TeV to 3.2 PeV in AMANDA-II and no excess was found. This allows for an upper limit of $E^2\Phi < 9.5 \times 10^{-8}$ cm^{-2} s^{-1} sr^{-1} GeV [9] to be determined. An all-flavor upper limit $E^2\Phi < 8.6 \times 10^{-7}$ cm^{-2} s^{-1} sr^{-1} GeV from the cascade channel has been determined [10] using AMANDA-II in the energy range 50 TeV $< E <$ 5 PeV. The most sensitive search for ultra-high energy neutrinos has produced the following upper limit: $E^2\Phi < 3.8 \times 10^{-7}$ cm^{-2} s^{-1} sr^{-1} GeV in the energy range of 0.18 PeV to 1.8 EeV with AMANDA-II [11].

Localized point-source searches have been conducted (see contributions included in [12]) including a time-rolling search for clustering with possible sources such as supernova remnants, microquasars, and TeV and GeV blazars, searches for time-correlation with TeV gamma ray sources and gamma ray bursts, and a so-called stacking source analysis using classes of active galactic nuclei. In all of these searches no statistically significant excess is seen. Searches for fluxes of muon neutrinos from the center of the Earth and the Sun have yielded nothing beyond the expected atmospheric background. Therefore, muon flux limits [13] have been derived. The 90% C.L. upper limits on the muon flux from neutralino annihilation found can be seen in figure 3.

4.3 *ANTARES*

The ANTARES project [14] began in 1996 and aims to construct a 0.1 km^3 volume neutrino telescope in the Mediterranean Sea off the coast of France. The full design calls for 12 strings, with 25 storeys per string and 3 optical modules per storey. Studies have been undertaken to characterize the light transmission properties of the deep-sea site [15] and to test deployment and hardware [16]. In February–March of 2006 ANTARES successfully deployed one instrumented string and reconstructed its first atmospheric muons.

4.4 *NEMO*

Another effort in the Mediterranean is the NEMO collaboration [17]. Their goal is the construction of a cubic-kilometer neutrino telescope off the coast of Italy. Current research and development will be ongoing this year in a so-called Phase 1 stage [18]. The test apparatus installed will consist of a four-storey tower; each storey will be 15 m long with two optical modules at each end. Also tested will be the data communication system, positioning system, and time calibration methods.

4.5 *NESTOR*

The NESTOR detector [19] is a proposed deep-sea neutrino telescope located off the coast of Greece. Planned deployment will be at a depth of 4000 meters. The full detector, with an effective area of 10^4 m^2 for $E_\mu \geq 10$ TeV, will be composed of towers each made up of 12 floors, with each floor having a structure of six hexagonal arms. The end of each arm has one upward-facing and one downward-facing optical module.

An initial deployment of a test floor was carried out in 2003 [20] with the purpose of testing the hardware and data aquisition and transmission. A measurement of the cosmic ray muon flux was made [21], in good agreement with previous measurements by other experiments.

4.6 *KM3NeT*

A proposed cubic-kilometer neutrino telescope project, called KM3NeT [22], will utilize and consolidate the expertise of the three smaller aforementioned Mediterranean projects. With a cubic-kilometer instrument in the southern hemisphere

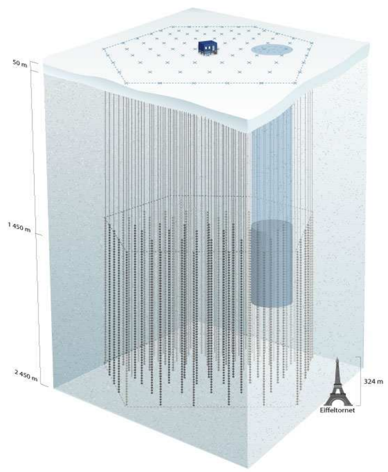

Figure 4. Geometry of full IceCube detector, including volume covered by AMANDA-II (highlighted cylinder) and IceTop.

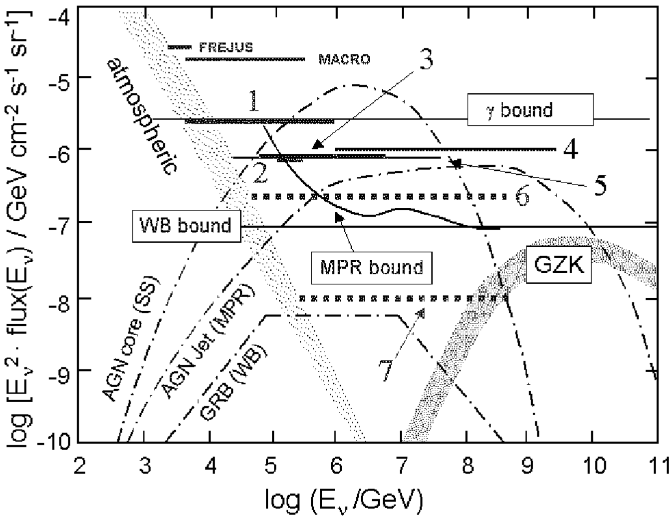

Figure 5. Summary of diffuse flux measurements and expectations compared with model predictions: (1) AMANDA B-10, muon tracks [26], (2) AMANDA-II, muon tracks, (3) AMANDA-II, cascades [10], (4) AMANDA-B10, UHE cascades [27], (5) NT-200, cascades [7], (6) AMANDA and NT-200+, expected 4-year sensitivity, (7) IceCube, expected 3-year sensitivity [28]. The implicit assumption is a $1:1:1$ flavor ratio at the Earth and an energy spectrum E^{-2}. ν_μ-only results are multiplied by three. Figure is from [29] and references to theoretical flux predictions can be found therein.

(IceCube), one in the northern hemisphere would give full-sky coverage (along with an eye toward the galactic center). KM3Net is currently at the beginning of an anticipated three-year research and development stage towards construction of an instrument located in the Mediterranean.

4.7 *IceCube*

A successful deployment season in austral summer 2004–2005 saw the installation of the first IceCube [23] string and 8 water Cherenkov surface detectors at the South Pole. Each kilometer-long string consists of 60 digital optical modules (DOMs) separated by 17 meters. Successful reconstruction of coincident cosmic ray events in coincidence with the in-ice string (events separated by a distance of up to 2.5 km) demonstrated the working of the detector and the ability to precisely reconstruct downward muons. Preliminary analysis of the data has also yielded two upward-going neutrino candidates. Performance studies of the deployed strings have shown that times can be determined with a relative precision of better than 3 ns. IceCube is also instrumented with LED flashers and lasers for use in calibration and testing of reconstruction algorithms. Further performance details can be found in [24].

The austral summer of 2005–2006 saw the successful deployment and operation of 8 additional strings and 12 more surface stations (consisting of two water Cherenkov detectors each). At its present size, with 9 strings, IceCube becomes the world's largest neutrino telescope.

One benefit of deployment in a large volume of ice such as that found in Antarctica is the ability to construct a complementary air shower array such as IceTop [25], which will eventually cover the surface of IceCube with 160 water Cherenkov detectors. Additionally, AMANDA-II is included in the IceCube detector volume and the data from both detectors is being studied in separate and coincident analyses. The full IceCube detector is shown in figure 4, where the cylindrical volume indicates the size and placement of AMANDA-II. The full detector, an anticipated 80 strings making up a cubic-kilometer of instrumented volume, is scheduled to be completed by 2011.

5. Conclusions

The present and future of neutrino astronomy is bright, as current telescopes have searched for point sources, placed limits on diffuse fluxes (the summary of the situation is seen in figure 5), and probed particle physics such as that found in indirect searches for dark matter. With cubic-kilometer instruments on the horizon hopefully the immediate future will see the discovery of the first extra-terrestrial high-energy neutrino source: making true neutrino astronomy possible.

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