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Science potential of the IceCube detector

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Abstract. We review the science possibilities of IceCube, the kilometer scale neutrino telescope to be constructed at the South Pole.

1 Introduction

The main goal of the IceCube project (Goldschmidt et al., 2001) is to extend the volume of the universe explored by neutrinos and thereby to test fundamental laws of physics, obtain a different view of astronomical objects, and to learn about the origin of the highest energy cosmic rays. The science topics include the search for steady and variable sources of high energy neutrinos like Active Galactic Nuclei (AGN) or Supernova Remnants (SNR) as well as the search for high energy neutrinos from transient sources like Supernovae or Gamma Ray Bursts (GRB).

Beside high energy neutrino astronomy, IceCube can tackle a series of other questions like the search for neutrinos from the decay of superheavy particles related to topological defects, the search for magnetic monopoles or other exotic particles like strange quark matter, the search for Weakly Interacting Massive Particles, and the monitoring our Galaxy for MeV neutrinos from supernova explosions.

We give a review of the expected physics capabilities of IceCube on each of the mentioned topics.

2 Search for extraterrestrial high energy neutrinos

a) Diffuse fluxes

Theoretical bounds on the diffuse flux of high energy neutrinos have been obtained from the normalization of neutrino fluxes to the cosmic ray spectrum and from the background of diffuse gamma rays. Bounds vary between $5 \cdot 10^{-8} \cdot E^{-2}$ (Waxman and Bahcall , 1999) and $10^{-6} \cdot E^{-2}$ (Mannheim, Protheroe, Rachen , 2000), both in units of $\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. Figure 1 summarizes various upper bounds and gives the best limit to be obtained with neutrino-induced muons in IceCube (Leuthold et al., 2001), which is about $2.7 \cdot 10^{-9} \cdot E^{-2}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}$ after 3 years of operation using present analysis algorithms and is expected to improved with advanced methods. (Alternatively, we search for neutrino-induced electromagnetic and hadronic showers (”cascades”), which have smaller effective volumes but better reconstruction efficiencies relative to muons.)

Mannheim and Learned (2000) have reviewed model predictions for AGN, GRB and other sources which range from a few events up to a few thousand events per year in a cubic kilometer detector.

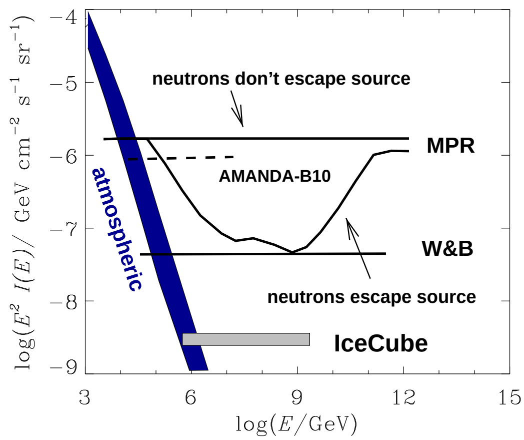

Fig. 1. Bounds derived from the observed flux of charged cosmic rays (WB= Waxman and Bahcall (1999), MPR=Mannheim, Protheroe, Rachen (2000), with MPR also under the assumption that sources are optically thick for neutrons. Theoretical bounds are compared to the flux of atmospheric neutrinos, the preliminary limit of AMANDA-B10, and the limit achievable with IceCube.

b) Point sources

In the case of a point source, the background from atmospheric neutrinos is reduced drastically. In contrast to the diffuse case, which is fully background dominated (Leuthold et

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al., 2001), the point source limit improves nearly linear with exposure time. For IceCube it is $7.3 \cdot E^{-2} 10^{-9}$ after 1 year and $3.2 \cdot 10^{-9}$ after 3 years (in units of $\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$).

This can be compared to gamma ray observations. Fluxes of Markarian 501 vary between 0.2 and $10 \cdot 10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for E >1.5 TeV, depending on the flaring phase (Weekes , 2000). Recent results (Wang et al., 2001) from MILAGRITO set an upper limit of $10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for declinations between 10 and 70 degrees and energies above one TeV.

The given limit of IceCube transforms to $F_\nu(>1\mathrm{TeV}) \sim 3 \cdot 10^{-12} \mathrm{cm}^{-2} \mathrm{s}^{-1}$ i.e., it is 1.5 orders of magnitude below the Milagrito limit for gamma rays and also below the observed Mk501 flux in the flaring phase.

The ratio of neutrinos to gamma rays can vary over a wide range. For a hadronic beam one expects $\nu/\gamma \sim 1$ if all primary gammas from π^o decay would escape the source region. Cascading of gammas in the surrounding medium results in a flux of low-energy gammas which is much higher than that of the primary high-energy neutrinos. If the source accelerates particles to EeV energies, one therefore would expect $\nu/\gamma \ll 1$ in the TeV range and $\nu/\gamma \gg 1$ at EeV energies. If the maximum energy of the accelerator is in the TeV-PeV range, ν/γ at TeV energies would be closer to unity. The ν/γ-ratio could be even larger than unity for "cocooned" sources. The ν/γ ratio and its dependence on energy tells us much about both the acceleration process (electron vs. hadron acceleration) and the character of the beam dump. Therefore IceCube observations with the sensitivity given above will put strong constrains on source models.

As recent examples, we mention two papers which have appeared since Mannheim and Learned (2000). Schuster et al. (2001) estimate the neutrino production from collimated, relativistic blast waves in AGN jets. The bulk of the neutrino emission is expected in the energy range between 100 GeV and a few TeV, and lasts for several hours up to a few weeks. Rates are about ten events per square kilometer. In another recent paper on neutrinos and photons from shock breakouts in supernovae (Waxman & Loeb , 2001), an hour-long flash of TeV neutrinos is predicted, about 10 hours after the thermal (MeV) neutrino burst. A km^2 telesope would detect about 10^2 muons.

c) Neutrinos from GRB

Waxman & Bahcall (1997) have proposed that GRB might be sources of neutrinos. The search for neutrinos is simplified over that for a point source due to the time stamp from satellite observations. In the Waxman-Bahcall model, neutrinos are expected to arrive within ~ 10 s of the gamma burst. For 1000 GRBs searched, a 10^o angular search bin and a 10 s time window, we would expect a total of 12 upgoing muon events, on top of a background of 0.23 fake events from downgoing muons.

Optimization of the cuts in the number of hit PMTs (see Leuthold et al. (2001)) leads to a cut at N_{ch}=12.5 (compared to 34 for the point source search and 180 for the diffuse flux). This corresponds to a model rejection factor *MRF* of 0.2 with respect to the Waxman-Bahcall limit, a severe constraint on the model. See Leuthold et al. (2001) for explanation of the *MRF*.

There are other models with higher signal predictions, see e.g. (Alvarez-Muñiz et al., 2000). We highlight a recent paper from Meszaros & Waxman (2001) who argue that for certain collapsar models of GRBs, multi-TeV neutrinos may emerge from an earlier (pre-burst) phase, from collisions of energetic photons with X-rays as a jet pushes through the envelope of the GRB progenitor. The predicted event rates range from a few hundred to a thousand per year over the full sky.

3 EeV physics

A kilometer-scale neutrino observatory, though optimized for detecting neutrinos of TeV to PeV energy, can be used for EeV science and reveal the science associated with the enigmatic supra-GKZ radiation in the Universe - see also Hundertmark et al. (2001). With the capability of measuring energy, IceCube can reject the atmospheric neutrino background by identifying the very high energy of cosmic neutrino events. As such, the instrument does not have to rely on the information that the neutrino penetrated the Earth. It therefore has sensitivity over a solid angle as large as 3π (or even more), including the horizon where most of the signal is concentrated. This is critical because up-going neutrinos carrying the energies of interest here are absorbed by the Earth. Calculations in the literature have thus routinely underestimated the event rates of IceCube for EeV signals by one to two orders of magnitude by calculating only the strongly absorbed flux of up-going neutrinos.

To benchmark the performance of IceCube we give the expected number of events per year for the following theorized sources of supra-EeV neutrinos (see Alvarez-Muñiz & Halzen (2001) and references therein). Eleven events per year are expected from generic topological defects assuming a grand-unified mass scale of order 10^{15} GeV and a particle decay spectrum consistent with all present observational constraints. Superheavy relics (Gelmini & Kusenko , 2000) would yield 30 events/year, with a normalization according to the Z-burst scenario (Weiler , 1999) where the observed cosmic rays with $\sim 10^{20}$ eV energy, and above, are locally produced by the interaction of ultra-energetic neutrinos with the cosmic neutrino background.

Note that these numbers are of the same order of magnitude as those expected for OWL (Cline & Stecker , 2000).

4 Detection of Tau Neutrinos

Since neutrinos are produced predominantly via pion decays, one expects a ratio $Q_{\nu_e} : Q_{\nu_\mu} : Q_{\nu_\tau} \sim 1 : 2 : 0$ at the source. Flavor oscillations during the flight to the Earth lead to a flux ratio $I_{\nu_e} : I_{\nu_\mu} : I_{\nu_\tau} \sim 1 : 1 : 1$, making the identification of high energy tau neutrinos an interesting challenge. CC interactions of tau neutrinos with multi-PeV energy would lead to a characteristic "double bang" signature, the first bang being due to the hadronic vertex of the ν_τ interaction, the second due to the τ decay (Learned & Pakvasa , 1995). For energies of several PeV, the τ lifetime is such that both bangs are well separated and still may occur inside the detector to provide an unmistakable signal for a high energy ν_τ. Because of the limited energy range and geometrical constraints, expected rates for these events are rather low, although there could be several tens of events per year in some topological defect scenarios. At much higher energy, one of the bursts would be too far outside the detector to be identified, but the event would still show up as a single large cascade if either the production or the decay of the τ lepton occurred inside the detector. These events, which would be mainly from near the horizontal or above, could possibly also be identified as a ν_τ because the track of the associated τ lepton (entering or leaving) would have a much lower rate of energy deposition than a muon of comparable energy.

5 Relativistic magnetic monopoles

A magnetic monopole with unit magnetic Dirac charge $g = 137/2 \cdot e$ and a velocity β close to 1 would emit Cherenkov radiation along its path, exceeding that of a bare relativistic muon by a factor of 8300 for $\beta = 1$ (Tompkins , 1965).

Observations of galactic magnetic fields, as well as observations matched with models for extragalactical fields, suggest that monopoles of cosmological origin with masses below 10^{15} GeV can be accelerated in these fields to relativistic velocities (Weiler , 2000). Figure 2 summarizes current limits. Note that most of these limits are below the Parker bound (10^{-15} cm^{-2} s^{-1} sr^{-1}).

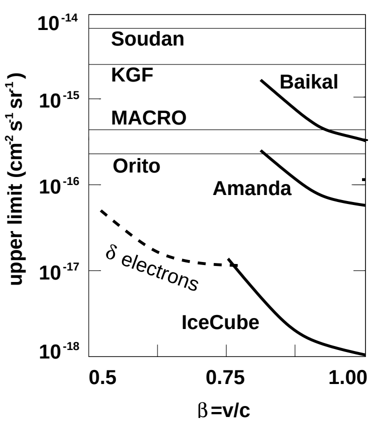

Fig. 2. Present limits on the flux of relativistic monopoles compared to limits achievable with IceCube.

A cube kilometer detector could improve the sensitivity of this search by about two orders of magnitude compared to the present Amanda limit. The search could be extended to down to velocities $\beta \sim 0.5$ by detecting the δ electrons generated along the monopole path.

6 Slowly moving, bright particles

The passage of a particle with a velocity significantly below c yields a very distinct time pattern. Candidates for particles with a velocity $\beta < 0.1$ are GUT magnetic monopoles or nuclearities. GUT monopoles may induce proton decays, yielding Cherenkov light signals generated by the nucleon decay products along their path. Nuclearities (strange quark matter) could have been produced in the primordial Universe or in violent astrophysical processes (Bakari et. al , 2000; Giacomelli & Patrizii , 1998) and would generate light via heating of the medium.

The best upper limits on the flux of these particles come from track etch experiments or liquid scintillator experiments. The Baikal experiment has searched for enhanced counting rates over time intervals of 500 μs and deduced upper limits on the flux of GUT monopoles and strange quark matter (Belolaptikov et. al (1997)). The search technique relies on detectors with a low counting rate (achieved by local coincidences in the Baikal case). With a counting rate per OM of 300 Hz (compared to typically 1 kHz for AMANDA), IceCube can also look for these phenomena.

7 Neutrinos from WIMP annihilation

If Weakly Interacting Massive Particles (WIMPs) contribute to dark matter, they would also populate the galactic halo of our own Galaxy. They would get captured by the Earth or the Sun where they would annihilate pairwise, producing high-energy muon neutrinos that can be searched for by neutrino telescopes. A favorite WIMP candidate is the lightest neutralino which arises in the Minimal Supersymmetric Standard Model (MSSM).

The typical energy of the neutrino-induced muons would be of the order of $\leq$ 25% of the neutralino mass. Since the threshold for muons from the direction of the Sun (i.e. close to the horizon) is $\sim$ 100 GeV, we expect IceCube to be sensitive to solar WIMPs heavier than about 400 GeV.

The sensitivity for WIMP detection depends on the WIMP mass as well as on the typical decay channel (”soft” channels from WIMP decays into many secondaries, ”hard” channels from decays into a few secondaries only). Figure 3 shows the predicted muon rates from WIMPs annihilating in the Sun as a function of the WIMP mass. Each symbol in the plot corresponds to one particular combination of MSSM parameters (with the WIMP mass being one of them). Lines indicate the limits which could be achieved with IceCube after 5 years of observation. Different symbols mark MSSM versions which are currently ruled out by direct detection experiments (dots), which could be seen by direct detection experiments if the sensitivity is increased by a factor of ten (+), and which could not be seen by present direct detection experiments even after a tenfold increase in sensitivity ($\times$). All values are normalized to 10 GeV threshold to allow for comparison[1]. IceCube

[1]For directions close to the vertical, the IceCube energy threshold indeed might be reduced below 20 GeV. Taken all strings to-

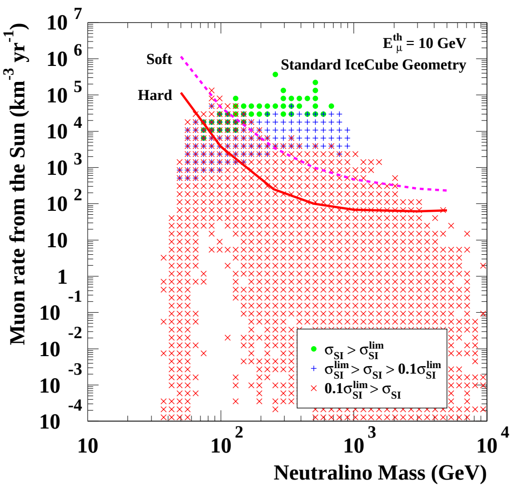

Fig. 3. The predicted muon rates from WIMPs annihilating in the the Sun as a function of the WIMP mass. See text for explanation.

could play a complementary role to future direct detection experiments (like CRESST or GENIUS) via WIMP annihilation in the Earth, and even has a slight advantage over direct detection experiments for certain low-mass WIMP models and annihilation in the Sun (Edsjo , 2000).

8 Neutrino oscillations

With a 10 megaton detector of 20 GeV threshold, IceCube may also play a role in confirming the compelling indications that atmospheric neutrinos oscillate. Studies of systematics and backgrounds have revealed that significant progress requires much smaller spacing of OMs along a string (4-6 m) than presently planned. For reduction of the threshold toward the horizon also a considerably smaller inter-string spacing would be necessary. Such specialized effort is only warranted if ongoing experiments fail to conclusively prove the oscillation hypothesis. In that case one would consider creating a densely equipped region for detection of low-energy contained events as one part of IceCube.

In recent papers (Dick et al. , 2000), the possibility is discussed to direct a neutrino beam at IceCube - either a Wide Band Beam or a beam from a neutrino factory. It has, however, to be investigated how well discrimination between muon tracks and cascades at low energies would work.

9 MeV neutrinos from Supernovae

Although the energies of electron anti-neutrinos from a supernova are far below the AMANDA/IceCube trigger threshold, a supernova would show up in higher counting rates of individual PMTs over a time window of 5-10 s. The enhancement in rate of *one* PMT will be buried in dark noise signals of that PMT. However, summing the signals from *all* PMTs over 10 s, significant excesses can be observed (Neunhoeffer et al , 2001).

Amanda is a member of the Supernova Early Warning System SNEWS (Scholberg , 2000). The role of Amanda will be to yield one of several coincident alarm signals from different detectors like Super-K, LVD and SNO. On top of that, IceCube might contribute to estimate the supernova direction by triangulation (Köpke & Weinheimer , 2000; Neunhoeffer et al , 2001). The resulting angular resolution depends on the orientation of the triangulation grid with respect to the supernova. For the three detectors Super-K, SNO and IceCube it would range between typical values of 5 to 20 degrees.

10 The Unexpected

As a detector more than thirty times larger than Amanda and about thousand times larger than underground detectors, IceCube will hopefully keep the promise for any detector opening a new window to the Universe: to detect phenomena *not* mentioned in this paper.

gether, one obtains a detection volume of 10 Megatons at a threshold of 20 GeV.

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