Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 51 (2013) 238–241
Advances in Space Research
(a COSPAR publication)
www.elsevier.com/locate/asr

The IceCube neutrino observatory: Status and initial results

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Available online 30 May 2011

Abstract

The IceCube neutrino observatory, now completed with a total of 86 strings deployed, is the world's largest high energy neutrino telescope. The detector instruments a cubic kilometer of Antarctic ice as a Cherenkov medium for the detection of neutrinos produced when cosmic rays interact with matter or radiation fields either near their acceleration sites or in the Earth's atmosphere. The results of searches for neutrinos from astrophysical objects such as supernova remnants, active galactic nuclei, and gamma ray bursts, using data from the partially built detector, are presented.
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Keywords: Neutrino astronomy; Galactic cosmic rays; Extragalactic cosmic rays

1. Introduction

Very high energy (VHE, $E > 100$ GeV) neutrinos from astrophysical objects can provide a clear indication of the origins of galactic and extragalactic cosmic rays. Neutrinos would be produced in these systems by accelerated hadrons, via *pp* or $p\gamma$ interactions, and would provide definitive evidence of cosmic ray acceleration. This is in contrast to the gamma rays which are currently our primary source of information about the VHE universe, but which can be produced through various mechanisms including electron inverse Compton scattering and other processes unrelated to accelerated cosmic rays.

The IceCube neutrino observatory, located at the South Pole, is the world's largest detector of VHE neutrinos. The observatory consists of 5160 digital optical modules (DOMs) sunk into the polar ice cap on 86 vertical cables, or 'strings,' at depths of 1450 m to 2450 m below the surface of the ice. In addition, the observatory contains a surface air shower array of 80 pairs of ice tanks, each 2 m in diameter and containing two DOMs, known as IceTop. Although the bulk of the buried detector is deployed on a uniform triangular grid of 125 m spacing, with 17 m spacing between consecutive DOMs on a string, eight of the 86 strings were deployed within the central hexagon of the array with 50 of the 60 DOMs on each string concentrated within the bottom 350 m of the strings. These eight strings, plus the seven regular strings forming the innermost hexagon, constitute DeepCore, a specialized array used to lower the energy threshold of the detector to facilitate studies of atmospheric neutrinos and searches for dark matter. The geometry of the detector is illustrated in Fig. 1.

IceCube operates by detecting charged leptons produced when VHE neutrinos undergo charged or neutral current interactions with nucleons in the ice. Cherenkov radiation emitted by the charged leptons is detected by 10" photomultiplier tubes (PMTs) in the DOMs, operated at a gain high enough to detect single photoelectrons. These photoelectrons are digitized by onboard waveform recorders and reported asynchronously to a software-based data acquisition system on the surface (Abbasi et al., 2009). The vast majority of the approximately 2 kHz trigger rate is due to atmospheric muons penetrating from above; neutrinos can be distinguished by searching for upgoing muons (necessarily produced by neutrinos which have passed through the Earth), for hadronic or electromagnetic cascades produced by neutral current, electron, or tau

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doi:10.1016/j.asr.2011.05.011

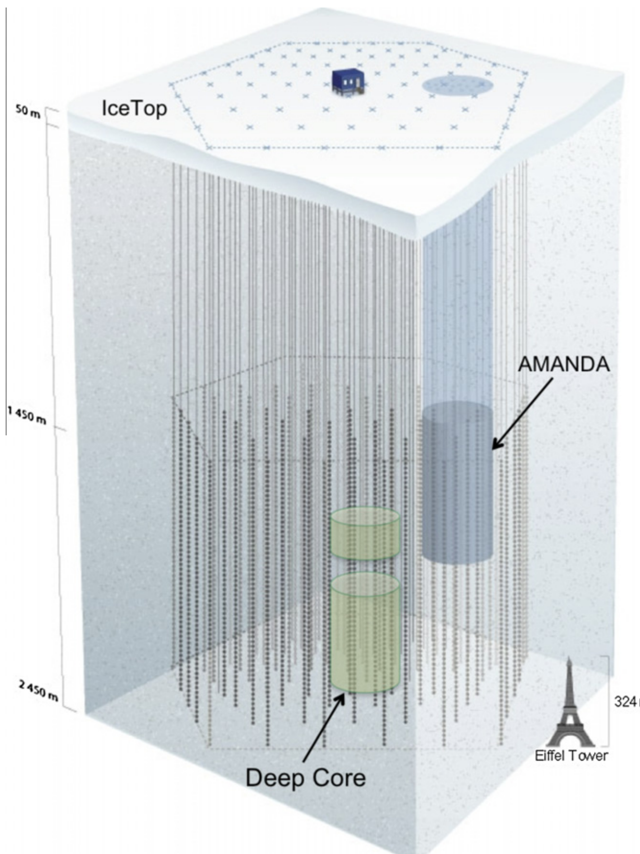

Fig. 1. Layout of the IceCube neutrino observatory. Each dot represents a DOM in the ice, or a pair of ice Cherenkov tanks in the IceTop surface array. The regions occupied by the DeepCore extension and the earlier AMANDA detector are indicated, but individual DOMs are not shown. Scale is given by the Eiffel Tower, at right.

neutrino events, for muons with energies higher than expected from the atmospheric muon flux, or for muon tracks originating at a neutrino interaction vertex within the detector.

The IceCube detector was deployed in stages during the austral summers (November–February) of 2004-10, when access to the South Pole is possible. Following each deployment, the detector was operated in its partially-deployed configuration, generally referred to by the number of strings then operational. Results from the IceCube-22 and IceCube-40 data runs (2007 and 2008) are presented here. In addition, the prototype AMANDA detector, deployed in the same volume as IceCube, was operated in conjunction with IceCube until being decommissioned in 2008, and some results from the combined operations are also included.

2. Searches for neutrino sources

The primary scientific goal of IceCube is the detection of individual astrophysical sources of neutrinos. Neutrinos from such sources must be distinguished from both the downgoing flux of atmospheric muons produced in cosmic ray showers in the Earth's atmosphere, and also the nearly uniform flux of atmospheric neutrinos produced by decaying mesons in those same air showers. IceCube is capable of searching for neutrino sources anywhere in the sky, although the techniques used and energy ranges accessible vary for the northern and southern sky. For potential sources in the Northern Hemisphere, the Earth serves as a filter for atmospheric muons, so the primary background is atmospheric neutrinos. For potential sources in the Southern sky, the dominant background of atmospheric muons is reduced by demanding very bright, high energy muon tracks, which comes at the cost of greatly reduced sensitivity to neutrinos below PeV energies. Because the spectra of Galactic cosmic ray accelerators are likely to peak at energies around or below the knee of the cosmic ray spectrum at a few PeV, neutrino telescopes in the Northern Hemisphere such as ANTARES (Aguilar et al., 2010) or KM3NeT (Katz et al., 2011), which can achieve higher sensitivity to neutrinos below the PeV scale, have an advantage in searching for accelerators in the inner Galaxy. In the future it may be possible to improve the response of IceCube to neutrinos from the southern sky at the TeV scale and below using DeepCore to identify muons produced by neutrinos interacting within the detector volume (Schulz et al., 2008), and to reduce the atmospheric neutrino background to these sources by vetoing muons produced in air showers accompanying these neutrinos (Schönert et al., 2009).

The preliminary results of a full-sky search for point sources of muon neutrinos using data from the IceCube-40 configuration, taken in 2008-09, is shown in Fig. 2. The search uses an unbinned likelihood analysis which includes the estimated angular reconstruction error and estimated energy of each event (Abbasi et al., 2010a). The most extreme p-value (i.e.; likelihood of an observation at least equally improbable under the null hypothesis) observed in the map is 5.2×10^{-6}, which must be interpreted in the context of the very large number of points tested. Such p-values are seen in 18% of randomized sky maps, indicating that the result is fully consistent with the background-only hypothesis. As a result of the sharply different energy ranges accessible above and below the horizon, the sensitivity of this search varies with declination, but ranges from 2×10^{-12} to 2×10^{-11} TeV cm^{-2} s^{-1} in the Northern Hemisphere and from 3×10^{-12} to 2×10^{-10} TeV cm^{-2} s^{-1} in the Southern Hemisphere, assuming unbroken E_ν^{-2} spectra.

In addition to searches for point sources, a search for more extended emission from the Cygnus region of the Galaxy was conducted using combined data from the IceCube-22 and AMANDA detectors, taken in 2007-08 (Sestayo et al., 2011). The Cygnus region, where the line of sight passes through the length of the Cygnus arm, is known to be a region of elevated gamma ray emission at TeV energies (Abdo et al., 2007), and neutrino emission from an ensemble of cosmic ray accelerators could potentially be detected. Because the number and location of

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