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Neutrino astrophysics with IceCube

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ABSTRACT

IceCube is a neutrino observatory in operation at the geographical South Pole. The main objective of IceCube is to conduct very-high-energy neutrino astronomy, including the search for the sources of cosmic rays. IceCube operates by measuring Cherenkov light from particles produced in neutrino–matter interactions. IceCube has made multiple observations including atmospheric neutrinos and cosmic ray anisotropy. For the first time, IceCube is reporting the observation of 28 events consistent with an astrophysical origin. The events have energies that range from ≈ 30 TeV to ≈ 1.2 PeV. The atmospheric origin of the events is excluded at the 4.1σlevel. In these proceedings we summarize the study of these 28 events. We also present the results of the search for neutrinos in coincidence with GRB 130427A.

1. Introduction

Cosmic rays are charged particles of unknown origin detected at Earth from all directions. Cosmic rays are observed from 10^9 eV to 10^{20} eV. Below $\sim 10^{14}$ eV, balloons and satellites directly observe cosmic rays and their elemental composition (i.e. protons, helium, …, iron isotopes) is well known [1]. At high energies, the steeply falling flux requires the use of larger and indirect ground based detectors, thus the composition is not so clear [2]. At the highest energies, there is disagreement on measurements by the Pierre Auger observatory and Telescope Array/HiRes [3,4]. The former implies that the highest energy cosmic rays are heavy isotopes (e.g. iron) and the latter data is consistent with light elements. IceCube itself has measured a spectrum in the region near 10^{16} eV that was reported in this conference [5]. Even minute anisotropies on the scale of a part per 10^3-10^4 have been observed [6–8] both over large (full sky) and medium scale ($\sim 10^\circ$). IceCube has also reported the observation of anisotropies of cosmic rays at this conference [9].

However, we still do not know with certainty what the sources of cosmic rays are. Because galactic magnetic fields trap cosmic rays in the disk, cosmic rays below the *knee* (4×10^{15} eV) are believed to be of galactic origin. The galactic cosmic rays may extend as high as the *ankle* (4×10^{18} eV). At even higher energies, cosmic rays are probably extra-galactic. For galactic cosmic rays there is significant circumstantial evidence that their source is supernova remnants. Part of the evidence is that the mechanical power of all ejecta of supernova remnants in our galaxy is about 2 order of magnitude higher than the power needed to keep the cosmic ray population. A mechanism, such as first order Fermi acceleration, which transfers kinetic energy into high energy particles with an efficiency of a few percent is sufficient to explain the origin of cosmic rays. Multiple gamma ray observations in the GeV and TeV scale are consistent with some supernova remnants being sources of cosmic rays. One such example is Tycho's supernova, [10] or SN1572. Furthermore GeV and TeV observations of gamma ray flux from nearby galaxies, including star burst galaxies, correlated the diffuse galactic gamma-ray flux with star formation rate [11,12]. And the supernova rate traces star formation rate.

Since there are mechanisms to produce GeV and TeV gamma rays that do not require cosmic ray acceleration, the observations with gamma rays are not conclusive [10]. Furthermore, if galactic cosmic rays extend up to the knee, it would be expected to see one or more supernova remnants that produce gamma rays up to 100 TeV. These supernova remnants have not been found yet. In the case of extragalactic cosmic rays, the situation is less clear. Multiple candidates exist such as active galactic nuclei, gamma-ray bursts and galaxy clusters.

On the other hand, neutrino observations are uniquely tied to cosmic rays interacting at or near their source. The main objective of IceCube – but not the only one – is to detect astrophysical neutrinos. Using these neutrinos we intend to find the sources of galactic and extragalactic cosmic rays.

These processing summarize recent observations by IceCube that provide the first evidence for very-high-energy neutrinos of astrophysical origin and perhaps a beginning of the understanding of the origin of cosmic rays.

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2. IceCube

IceCube is a neutrino telescope operating at the South Pole. IceCube detects secondary charged particles produced in neutrino–matter interactions. When a very-high-energy charged particle travels through the very clear antarctic ice, it produced blue Cherenkov radiation. IceCube consists of a 3-dimensional array of optical sensors, called digital optical modules (DOMs), that sense the Cherenkov light. Each DOM consists of a photo-multiplier tube (PMT), digitizing electronics inside of a transparent pressure sphere. A total of 5160 DOMs have been installed at depths ranging from 1450 m to 2450 m arranged in 86 vertical strings. A subset of these strings have been deployed closer to each other with smaller DOM to DOM vertical separation. This subset of strings is known as DeepCore. The nominal threshold of IceCube is 1 TeV, the higher DOM density and the use of high quantum efficiency PMTs lowers the DeepCore nominal threshold to 10 GeV. The rest of IceCube fully surrounds DeepCore, thus providing a very large veto for down-going muons and opening the full 4π sr sky to DeepCore. South Pole ice is highly transparent with optical properties that are depth dependent and trace the climate over the past 120 kyears. Typical absorption lengths are 100–140 m and typical effective scattering lengths are 25–35 m. A surface air shower array, known as IceTop, is another sub-detector of IceCube. It consists of 81 pairs of tanks filled with transparent ice and monitored by 2 DOMs each. As particles from extensive air shower arrays pass through IceTop tanks, they produce Cherenkov radiation. IceTop has three main objectives: measuring the cosmic ray spectrum and composition near the knee, calibrating IceCube and vetoing air showers.

IceCube construction began on 2005 and finished in December 2010. It is operated in approximately year-long campaigns. Since each string is independent, operations began along with construction. In these proceedings the moniker IC-XX indicates the data taking season for which IceCube had XX strings in operation. Currently IceCube is operating with very high duty cycle, e.g. 99.32% during April 2013, the month preceding the conference and $\approx 99\%$ of DOMs are operational. Because of low temperature and virtually zero natural radioactive background, PMT rates are very low. Using an artificial deadtime to reduce afterpulses, the rate is 300–500 Hz. This low rate provides the capability of detecting MeV neutrinos from supernovae anywhere in our galaxy and the Magellanic Clouds. Fig. 1 shows an schematic of IceCube, DeepCore and IceTop.

IceCube detects neutrinos via two main channels. In the *muon channel*, charged current interactions of $\nu_\mu(\overline{\nu}_\mu)$ in the ice or the bedrock under the detector result in an energetic muon and a hadronic particle shower. In these proceedings we refer to $\overline{\nu}$ and ν as neutrinos, since IceCube is insensitive to the difference, except at the 6.3 PeV Glashow resonance. A small fraction of expected astrophysical muon channel detections may come from ν_τ charged current interactions, since a τ decay leads to a muon with a branching ratio of 17.4%. The effective size of the detector is significantly increased by the long muon range. In the energies relevant to IceCube, muons can travel several kilometers through ice or rock. The neutrino interaction vertex often is outside of the detector for the muon channel. Muons can be reconstructed with degree accuracy given their long lever arm in IceCube, and the muon direction is highly correlated with the ν_μ direction: $\psi_{\nu-\mu} 0.7^\circ \sqrt{\mathrm{TeV}/E_\nu}$. The muon channel cannot measure the neutrino energy directly since the event is only partially contained.

The *cascade or shower channel* is the other main detection mode. Cascades are produced by all neutrino flavors via several mechanisms. These mechanisms include $\overline{\nu}_e + e^-$ interactions 6.3 PeV, i.e. the Glashow resonance; ν_e charged current interactions and neutral current interactions for all flavors. A high fraction of ν_τ charged current interactions also lead to cascades. In particular when the τ decays into mesons (64% branching ratio) or an electron (18% branching ratio). If the τ energy is below ≈ 100 TeV, it will travel ≈ 5 m. Then the initial neutrino–matter shower will overlap with the τ decay shower and it will be indistinguishable for IceCube from an isolated shower. At energies higher than ~ 1 PeV, ν_τ interactions lead to more complicated topologies that are combinations of showers and tracks [13]. A unique advantage of the cascade channel is that the event is

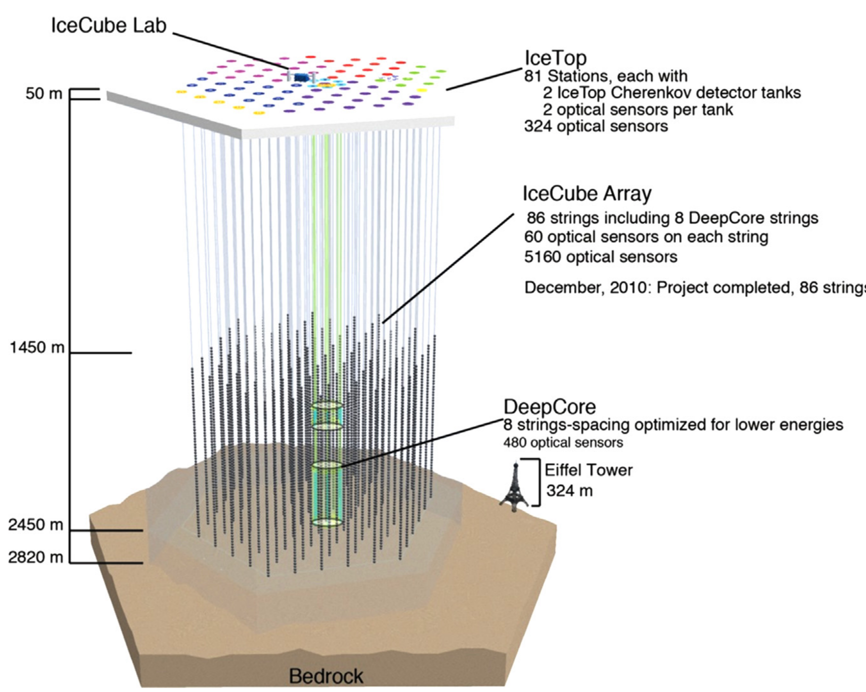

Fig. 1. The IceCube neutrino observatory. The main component consists of 86 strings with optical sensors between 1450 m and 2450 m of depth. A subset of these strings have been installed with denser vertical and horizontal spacing and placed near the center and bottom of IceCube. These strings form DeepCore. At the surface a set of 81 pairs of tanks constitute IceTop, an extensive air shower array.