DOI: 10.22661/AAPPSBL.2018.28.5.09

IceCube Neutrino Telescope Points to Sources of High-energy Cosmic Rays

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ABSTRACT

Groups in the Asia-Pacific are celebrating the latest breakthrough from the IceCube neutrino telescope which recently presented the first evidence for high-energy neutrinos from an astrophysical source. On September 22nd 2017, the Fermi and MAGIC gamma ray telescopes followed up an IceCube alert of a high-energy neutrino event and found that it was consistent in direction with the blazar TXS 0506-056 which was observed to be in a flaring state. Moreover, in a subsequent analysis of archival IceCube data, an excess of high-energy neutrino events with respect to atmospheric backgrounds was found at the position of TXS 0506-056 between September 2014 and March 2015. These results suggest that blazars are the first identifiable sources of high-energy astrophysical neutrinos.

INTRODUCTION

The Universities of Adelaide, Canterbury, Chiba and Sungkyunkwan University are members of the IceCube collaboration which operates the IceCube neutrino telescope at the South Pole [1]. A key design goal for IceCube was to identify the sources of high-energy cosmic rays and the latest results from IceCube suggest that the answer to this century-old mystery may be at hand. Due to their electric charge the paths of all but the highest-energy cosmic rays are deflected by cosmic magnetic fields meaning that the direction from which cosmic rays enter the atmosphere cannot be used to determine their origin.

However, cosmic rays interacting with radiation fields and matter close to their source would give rise to a flux of high-energy pions that eventually decay into photons and neutrinos. While high-energy photons may be absorbed at the source or through interactions with extragalactic background light, neutrinos travel from the sources largely unhindered by matter and radiation. However, because they interact so weakly, a large detector is needed to observe astrophysical neutrinos. Estimates of the expected astrophysical neutrino flux from the measured cosmic ray flux [2] suggested that a cubic kilometre detector would be necessary and motivated the construction of the IceCube neutrino telescope.

ICECUBE NEUTRINO TELESCOPE

IceCube consists of a cubic kilometre of Antarctic ice at the South Pole, instrumented with 5,160 digital optical modules (DOMs) [1]. The DOMs are deployed on 86 vertical strings, each holding 60 modules. Severty-eight of the strings are distributed on a 125 m triangular grid, covering about 1 km^2, with the DOMs spaced every 17 metres between 1450 and 2450 m below the surface. The remaining 8 strings, called “Deep Core” [3] are deployed near the centre of the array. They have smaller string-to-string and DOM-to-DOM spacing, giving Deep Core a lower energy threshold than the rest of the detector. A schematic of the IceCube detector is shown in Fig. 1. The DOMs observe the Cherenkov radiation emitted by the charged particles that are produced when neutrinos interact in the ice. In particular, the interaction of muon neutrinos can produce muons which travel several kilometres through the ice. The track of the muon can be deduced from the pattern of its Cherenkov light detected by the DOMs. More details of the IceCube neutrino telescope were described previously in this journal

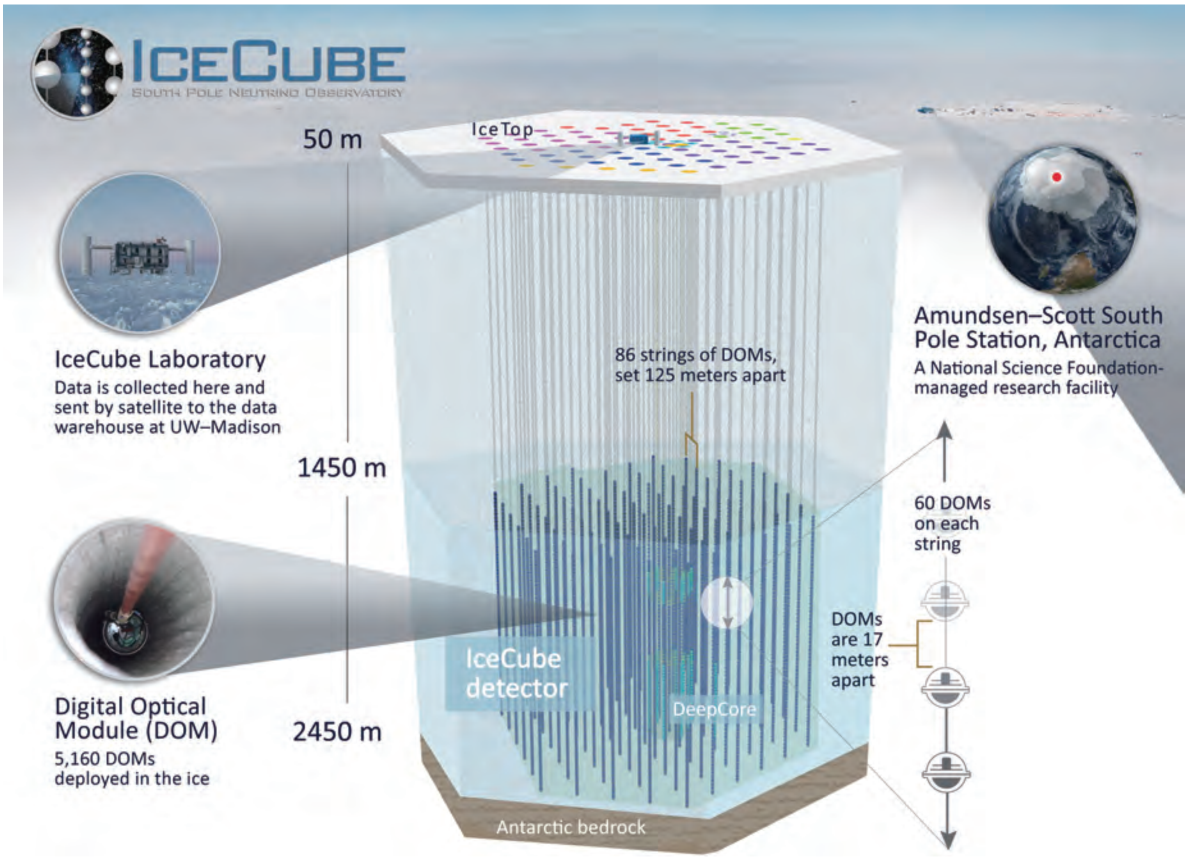

Fig.1: Schematic of the IceCube Observatory located at the South Pole.

where its use for indirect dark matter searches was presented [4].

ASTROPHYSICAL NEUTRINO SEARCHES

In 2013 IceCube presented the first observation of high-energy neutrinos of astrophysical origin, revolutionising astroparticle physics and opening a new window to the Universe [5].

Once the need for a huge detector is overcome, there is still a large challenge in astrophysical neutrino searches in that they must contend with two types of backgrounds created by cosmic rays interacting in the Earth's atmosphere. The first are downward-going cosmic-ray muons, which are a factor of around 106 more abundant than neutrinos, with IceCube triggering at about 2800 Hz, mostly from these muons. Two main strategies are employed to remove this background; either to select only upward-going tracks, since the Earth is opaque to muons, or to select events that originate within the detector, with no sign of an incoming track.

The second background is from atmospheric neutrinos, produced in cosmic-ray air showers. Because atmospheric neutrinos are produced in cosmic-ray air showers, they are likely to be accompanied by air shower particles and cosmic-ray muons; these additional particles may be used to veto downward-going atmospheric neutrinos [6,7,8]. Also, the astrophysical spectrum falls more slowly with energy than the atmospheric neutrino spectrum, so that although atmospheric neutrinos are dominant at energies below 100 TeV, astrophysical neutrinos are dominant at higher energies.

The neutrino filtering strategy which was effective in first identifying astrophysical neutrinos is the High Energy Starting Event (HESE) search [5,9,10]. Neutrino candidates were selected by finding events that originated within the detector interior. The HESE criteria for keeping an event was that at least 6,000 photoelectrons had to be recorded in total and fewer than three of the first 250 could be located in the veto region where the veto region was defined to be the outer parts of the instrumented volume. This event selection rejects 99.999% of

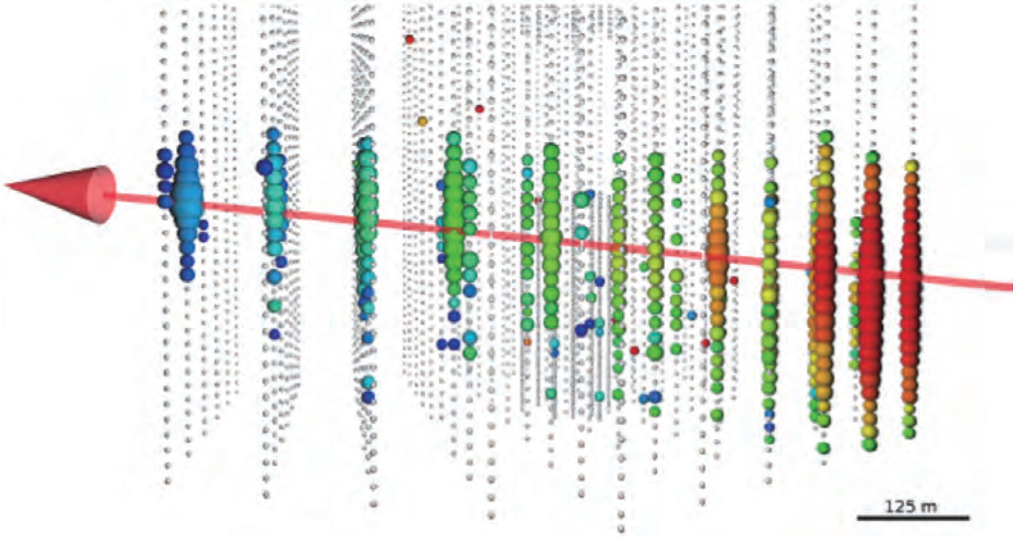

Fig. 2: Event view of IceCube-170922.

the muon background above 6000 photoelectrons while retaining nearly all neutrino events interacting within the fiducial volume at energies above a few hundred TeV. Subsequent searches using the upward-going muon strategy confirmed the detection of a flux of astrophysical neutrinos [11].

NEUTRINO SOURCE IDENTIFICATION

Despite the strong evidence for a flux of astrophysical neutrinos, until recently, searches for the sources of the neutrinos had not been able to associate any known objects with the neutrino events. Source search strategies include spatial and temporal correlation studies with neutrino events alone and seeking correlations between neutrino directions and catalogues of different classes of astrophysical objects [12,13,14].

In order to facilitate the identification of an electromagnetic counterpart to the astrophysical neutrinos observed, the IceCube collaboration has a number of follow-up programmes in place which include a real-time alert system to notify the high-energy astrophysics community of the detection of neutrinos enabling rapid follow-up observations [15]. Given the large background of cosmic-ray induced muon events detected by IceCube, the first challenge of the real-time alert system is to select a sufficiently pure sample of neutrinos, while the second is to identify the small fraction of neutrinos that are likely to be astrophysical in origin rather than atmospheric neutrinos. Two approaches are used; in the first, notifications are released if there are bursts of several neutrino-like events and the second approach is to issue alerts for particularly well-reconstructed events which have a high probability of being an astrophysical neutrino. In the second approach two different event filters are used to identify candidates, one is based on the HESE strategy mentioned above and the other is the Extremely High Energy (EHE) event filter which, as the name suggests, selects events with particularly high energies [15].

On September 22, 2017, IceCube sent a public alert reporting a neutrino-candidate event, IceCube-170922A, selected by the EHE online event filter. Such alerts are currently sent at a rate of about four per year with the selection threshold set so that approximately half of the events are estimated to be astrophysical neutrinos, the rest being atmospheric background events. It was soon determined that the direction of IceCube-170922A was coincident with a blazar, TXS 0506+056 [16].

Blazars are Active Galactic Nuclei (AGN) with relativistic jets oriented nearly towards the observer. In these AGNs, the central supermassive black hole converts gravitational energy of accreting matter and/or the rotational energy of the black hole into powerful relativistic jets. These jets have long been recognised as regions within which particles could be accelerated to high energies and thus are candidates for the sources of high-energy cosmic rays.

TXS 0506+056 was observed by the Large Area Telescope on the Fermi Gamma-ray Space Telescope [17] to be in a state of enhanced gamma-ray activity since April 2017 [18]. Follow-up observations of the blazar led to the detection of gamma rays with energies up to 400 GeV by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) Telescopes [19,20]. The chance coincidence of an IceCube neutrino event such as IC-170922A and finding a blazar in a flaring state at the same location has been disfavoured at the level of 3 sigma [16].

The event display for the neutrino event IceCube-170922A is shown in Fig. 2. Each coloured sphere indicates a hit DOM. The time at which a DOM observed a signal is reflected in the colour of the hit, with dark blues for earliest hits and yellow for latest. Times shown are relative to the first DOM hit. The total time the event took to cross the detector is 3000 ns. The size of a coloured sphere is proportional to the logarithm of the amount of light observed at the DOM. The best-fitting track direction is shown as an arrow and indicates the path of the muon produced when the neutrino interacted. The total charge recorded is 5800 photoelectrons which translates to an energy of 23.7 ± 2.8 TeV deposited in IceCube by the traversing muon. To estimate the energy of the parent neutrino, simulations of the response of the detector array are performed, considering that the muon-neutrino might have interacted outside the detector at an unknown distance. These simulations yield a most probable neutrino energy of 290 TeV, with a 90% confidence level lower limit of 183 TeV.

Prompted by the association of IceCube-170922A with TXS-0506+065, IceCube investigated 9.5 years of neutrino observations to search for excess emission at the position of the blazar [21]. No additional excess of neutrinos was found from the direction of TXS 0506+056 near the time of the alert. However an excess of high-energy neutrino events with respect to a random distribution of arrival directions at that position was found for the period between September 2014 and March 2015. Allowing for a time-variable flux, this constitutes 3.5 sigma evidence for neutrino emission from the direction of TXS 0506+056, independent of and prior to the 2017 flaring episode [21].

Earlier studies seeking a correlation between IceCube events and the blazar population observed by Fermi-LAT demonstrated that these blazars can only produce a fraction of the observed astrophysical neutrino flux above 10 TeV [14]. Although these limits constrain the contribution from blazars to the diffuse neutrino background, the association of one or two high-energy neutrinos over the total observing time of IceCube is completely compatible with the constraint.

The two analyses, the analysis of the single neutrino event IceCube-170922A event in correlation with electromagnetic activity and the archival analysis relying on self-correlation of multiple neutrinos, are statistically independent. The coincidence of an IceCube alert with a γ-ray flaring blazar combined with a neutrino flare from the same object gives strong support for the blazar TXS-0506+065 as a source of high-energy neutrinos and by association a source of high-energy cosmic rays. This new milestone in IceCube results may be the long awaited breakthrough in the 100 year-old mystery of the origin of cosmic rays.

FUTURE PLANS

The IceCube collaboration is eager to discover more high-energy neutrino sources. Many improvements to the detector are planned to enable this. The Asia Pacific institutions are contributing with a range of initiatives. For example, new algorithms for better determination of the neutrino properties are being advanced at the University of Adelaide while at the University of Canterbury work is underway on surface detectors to improve the atmospheric background rejection. New optical sensors designed at the University of Chiba will greatly improve the detection efficiency and a camera system developed at Sungkyunkwan University will allow a much enhanced calibration of the ice medium. Equipped with their experience and plans for the future, the IceCube collaboration is looking forward to many more exciting breakthroughs in high-energy astronomy.

Acknowledgements: The IceCube collaboration has received major support from the US National Science Foundation and European funding agencies. The Asia-Pacific Institutions are grateful for assistance from the Australian Research Council; Japan Society for Promotion of Science (JSPS) and Institute for Global Prominent Research (IGPR) of Chiba University; National Research Foundation of Korea (NRF) and the New Zealand Marsden Fund.

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(left to right) **Jenni Adams** is the PI of the University of Canterbury IceCube group. She has been at the University of Canterbury for 20 years, and for much of this time has been working on neutrino detection with a particular focus on cascade searches and background rejection with surface arrays. **Gary Hill** is an Associate Professor at the University of Adelaide, and was inaugural analysis coordinator for the IceCube Collaboration. He spent seven seasons at the South Pole constructing the IceCube detector. **Carsten Rott** is an Associate Professor at Sungkyunkwan University and a co-convener of the beyond standard model working group of the IceCube Experiment. He received his Ph.D. from Purdue University and worked at the Pennsylvania State University and the Ohio State University. **Shigeru Yoshida** is a Professor at the University of Chiba where he has been working on IceCube since 2002, with a focus on hunting for super energetic neutrinos. To realise IceCube's goals he is working on upgrading the IceCube detector elements.