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Search strategies for discovering extraterrestrial neutrinos with IceCube

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ABSTRACT

With completion expected in 2011, the IceCube Neutrino Observatory is approaching the 1 km^3 scale required for high energy neutrino astronomy. Before completion, the data taken with the deployed strings of the IceCube detector allows the testing of different procedures of searching for high energy neutrinos of extraterrestrial origin. This work describes some of the approaches used by the IceCube collaboration to search for point-like and extended sources. Emphasis will be placed on the results obtained from the analysis of the Cygnus region using data from the combined detector configuration IceCube-22-strings and AMANDA. The method presented here uses a two-point analysis to detect, within an extended region, event patterns which might go undetected in conventional point-source analysis.

1. Introduction

In the field of high energy neutrino astronomy, the current data analyses of the IceCube detector are approaching the realistic possibility of discovery of the first extraterrestrial neutrino source. At the current stage of development, in which the final data samples are dominated by atmospheric neutrinos, simple descriptive analysis of the data are not satisfactory, and the analyst has to resort to statistical analysis to improve the discovery potential. In this approach, a statistical description of the background and signal is used, and the result of the analysis returns the probability that the observed pattern is compatible with the background hypothesis.

The current search strategies are based on the fact that events produced by atmospheric neutrinos are random, uniformly distributed through the sky and over time, following a distribution in energy according to $\sim E^{-3.7}$. Possible neutrino events from astrophysical sources are expected to have a harder energy spectrum. They are also expected to form clustered patterns due to a number of reasons:

- Interaction of cosmic-rays close to their sources of origin.
- Massive stars, the progenitors of what is believed are the galactic accelerators of cosmic rays, are not located at random, but in clusters and associations. If cosmic rays interact before they escape, the neutrino sources resulting from this process will show a clustered pattern.
- Diffuse galactic cosmic rays interacting in regions of enhanced matter density will also produce neutrinos from the densest regions.
- The pattern is a result of the superposition of a number of neutrino sources located a different distances and appearing in a relatively small area of the sky. This case is particularly relevant in the Galactic Plane.

Spatial astrophysical neutrino data may therefore be of various broad types. Groups of events can be defined by their shape, may be clustered around points, lines, or show more complicated morphologies. Current analysis methods follow the search for clustering of events around single point sources, either in an all-sky survey mode or targeting potential candidates for neutrino emission [1–3]. However, astrophysical events which cluster at larger scales, like associations of neutrino sources, and/or following different morphologies (not point-like) can produce signals which might be missed by dedicated point-like searches. In order to cover these scenarios, we have developed an analysis which: (1) is model independent, being able to perform optimally under different types of event patterns and (2) takes advantage of the full signal content from an extended region, being able to lower our detection threshold with respect to single hot spot searches.

This approach was generated in order to study the neutrino event pattern in the Cygnus star forming region of our galaxy. This region, located between galactic longitude $65^\circ < l < 85^\circ$ is a good example of superposition of potential neutrino sources plus diffuse emission which are physically separated by several kpc but appear together on the sky. Our line of sight to Cygnus is

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almost parallel to the Local spiral arm, which causes all the massive star formation regions and potential neutrino sources appear in a projected area of $\sim 20^\circ \times 8^\circ$. The presence of this region in the high-energy gamma-ray sky [4] drives the development of an efficient method of studying the event pattern in this region.

2. Spatial analysis in neutrino telescopes

The techniques for the discovery of extraterrestrial neutrinos which cluster (diffuse analyses are not considered here) can be divided into two main groups:

- *Hot spot searches*: concerned with identifying hot spots, defined as a spatial concentration of events. The scale of the search depends on the size of the area under investigation.
- *Two-point analysis* (*distance analysis*): allow to determine how clustered or dispersed are the events compared to a given distribution of random events.

2.1. Hot spots analysis

The identification of hot spots is the most common motivation for the data analysis in high energy astrophysics experiments, since it allows one to localize the sources of the extraterrestrial events. It is commonly approached by mapping the sky in different ways:

- *Binned method*: is the simplest of the various hot spot techniques. It counts the number of events within a certain area. This method provides event density maps to identify hot spots. In the case of extended regions, the amount of background integrated with this technique makes the discovery of possible faint sources challenging.
- *Mixture models*: Deals with events which can be in one or several components, but we do not know which. The statistical description of the data is expressed as a mixture of N probability distributions: the background component and $N-1$ signal components. The form and the number (N) of the PDFs are assumed to be known. The signal components are usually assumed as Gaussians defined by a mean and variance. In IceCube this approach has been used for the search of single point sources ($N=2$) at specific locations in the sky (unbinned method). It is powerful for the cases where the sources to be identified are well separated "blobs" in space. This analysis provide probability maps according to the model considered.

2.2. Two-point analysis

Two-point analysis compare distances between the observed events with the expected distances from a random distribution of events. The resulting calculations indicate whether the events are significantly clustered. The most commonly used statistics to measure clustering are [5]:

- Distance to kth nearest event: uses the distance of each point to the kth nearest event, determines the mean distance and compares it with what would have been expected in a random kth nearest distribution.
- Two-point correlation functions and its variants. Defined as the excess with respect to a random distribution in the probability of finding an event within a certain distance from another event.

The advantage of these types of analysis is that the emission from various weak sources can be summed up and hence the discovery potential can be improved.

3. The Cygnus region in neutrinos with IceCube-22 +AMANDA

If there are neutrino events from astrophysical sources within the Cygnus region, they will produce variations in the local event density that will generate a more clustered event pattern than the one expected for background events. In order to detect neutrinos from this region, a region of $11^\circ \times 7^\circ$ between the galactic coordinates $72^\circ < l < 83^\circ$, $-3^\circ < b < 4^\circ$, the most active part of the Cygnus complex, is subjected to a dedicated analysis of the spatial event pattern using the data obtained during the 2007–2008 operation period of the combined detector IceCube 22 strings (IC22) plus AMANDA.

3.1. Multi-Point Source analysis for extended regions (MPS)

The MPS uses a two-point analysis to detect, within regions larger than IceCube's angular resolution, event patterns which depart from a random distribution of events.

A good estimator of the spatial correlations between events is the excess in the number of event pairs as function of the angular distance between the events in the pair. In MPS the distance (θ_{ij}) from an event i located inside the region to an event j (at any location) is measured at each of the N_{inside} events present in the region ($i=1,\ldots,N_{inside}$; $j=1,\ldots,N_{total}$). The number of pairs ij is measured and the histogram of event pairs as a function of the angular distance θ_{ij} is constructed from these measurements and compared with the one obtained from a random distribution of events. With this definition, the MPS can be interpreted as a two-point sampling of the area under study with bins of variable radius θ_{ij} centered at the positions of each the events inside the region.

The MPS returns a quantity that we define as "clustering index" as function of the angular distance. The clustering index represents the ratio between the histogram of pair distances in the data case and in the average random case. A score of 1 in the clustering index would indicate no discrepancy between the expected number of pairs in a random distribution and the measured number of pairs in the actual distribution. Scores higher than 1 indicate that events are more clustered than would be expected in a random distribution, and scores lower than 1 would

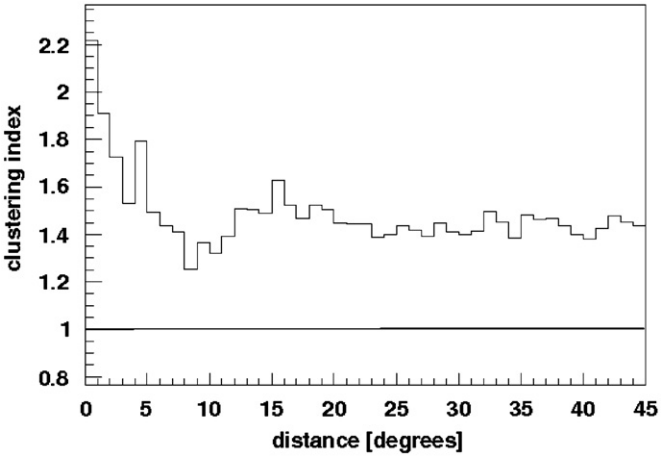

Fig. 1. Measured clustering index in the Cygnus region as function of the angular distance. The data shows an excess with respect to the average random distribution of events (located at 1) compatible with a fluctuation of the background at 2.3σ level.