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Indian Institute of Technology Hyderabad

ICE-CUBE DATA ANALYSIS

B.Tech. Project - Fall 2022

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ABSTRACT

The objective of this project was to determine angular correlation between radio pulsars and ultra-high energy neutrinos using the publicly available IceCube point source neutrino events catalog. For this purpose we use the unbinned maximum likelihood method to search for a statistically significant excess from each of the pulsars in the ATNF catalog.

1 INTRODUCTION

1.1 Pulsars

Pulsars are rapidly spinning neutron stars, which emit pulsed radio emissions with periods ranging from milliseconds to a few seconds with magnetic fields ranging from 10^8 to 10^{14} G. They are formed when massive rotating stars ($M \approx 12 - 15M_\odot$) undergo supernovae leaving behind a small, dense core($M \approx 2 - 3.4M_\odot$) supported by neutron degeneracy pressure. The collapsed core (comprised entirely of neutrons, hence, neutron star) retains most of the progenitor's angular momentum, while their moment of inertia is reduced sharply increasing their angular velocity.

1.2 Neutrinos

Neutrinos are fermionic particles that interact only via weak interactions and gravity. They are electrically neutral and have negligible rest mass.
Neutrinos are created by various radioactive decays, some of those processes which are observed often are:

1. Beta decay of atomic nuclei or hadrons
2. Natural nuclear reactions (such as those that take place in the core of a star)
3. Artificial nuclear reactions in nuclear reactors, nuclear bombs, or particle accelerators
4. During a supernova
5. During the spin-down of a neutron star
6. When cosmic rays or accelerated particle beams strike atoms

Neutrinos come in 3 *flavours*:

1. e^-
2. μ-on
3. τ

reference https://en.wikipedia.org/wiki/Neutrino

1.3 Neutrino detection methods

Due to their negligible rest mass, the gravitational forces exerted by neutrinos cannot be used as a way to detect them. So they are detected with their interactions with matter.
Neutrinos interact with matter in two ways

1. Neutral current interaction:
   In a neutral current interaction, the neutrino enters and transferres some of its energy and momentum to a 'target' particle, and leaves the detector. If the target particle is charged and sufficiently lightweight, it might be accelerated to a relativistic speed and consequently emit Cherenkov radiation, which can be observed directly.
   However, this detection does not enable us to determine the *flavour* of the neutrino
2. Charged current interaction
   In a charged current interaction, a high-energy neutrino transforms into its partner lepton

(e^-, μ, or τ). However, if the neutrino does not have sufficient energy to create its heavier partner's mass, it cannot undergo a charged current interaction.

1.4 IceCube

The IceCube is a neutrino observatory constructed at the Amundsen–Scott South Pole Station in Antarctica.

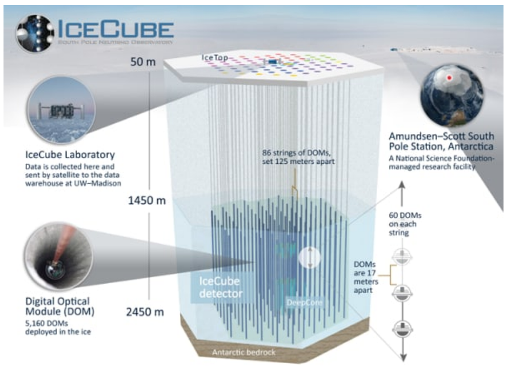

Figure 1

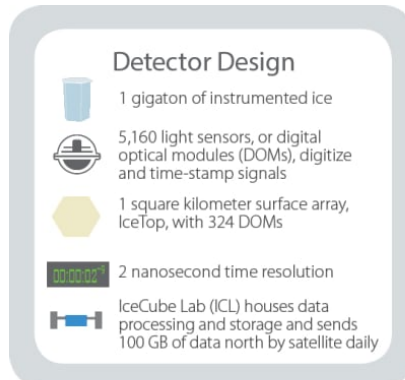

Figure 2

Structure of IceCube Observatory

The IceCube consists of 5,160 digital optical modules (DOMs), each with a ten-inch photomultiplier tube and associated electronics. The DOMs are attached to vertical "strings," frozen into 86 boreholes, and arrayed over a cubic kilometer from 1,450 meters to 2,450 meters depth. The strings are deployed on a hexagonal grid with 125 meters spacing and hold 60 DOMs each. The vertical separation of the DOMs is 17 meters.

1.5 Working principle

The IceCube detects neutrinos via the Neutral current interactions. When they happen to interact with the ice they produce electrically charged leptons that in turn emit Cherenkov light, as a result of traveling through the ice faster than light travels in ice.

The IceCube sensors collect this light, which is subsequently digitized and time stamped. This information is sent to computers in the IceCube Lab on the surface, which converts the messages from individual DOMs into light patterns that reveal the direction and energy of muons and neutrinos.

When neutrinos (rarely) collide with the molecules of ice, they create charged leptons (e^- μons and τ). If the created leptons are energetic enough, they emit Cherenkov radiation which is detected by photomultiplier tubes within the DOMs making up IceCube.

The IceCube is more sensitive to muons due to their greater penetration and longer detector tracks than other particles. An electron produced by an electron neutrino event to point back to sources because it scatters multiple times and loses energy below the Cherenkov threshold.

The IceCube is more sensitive to muons than others as they are the most penetrating and have the longest tracks in the detector. An electron resulting from an electron neutrino event scatters several times and loses enough energy to fall below the Cherenkov threshold, so they cannot be

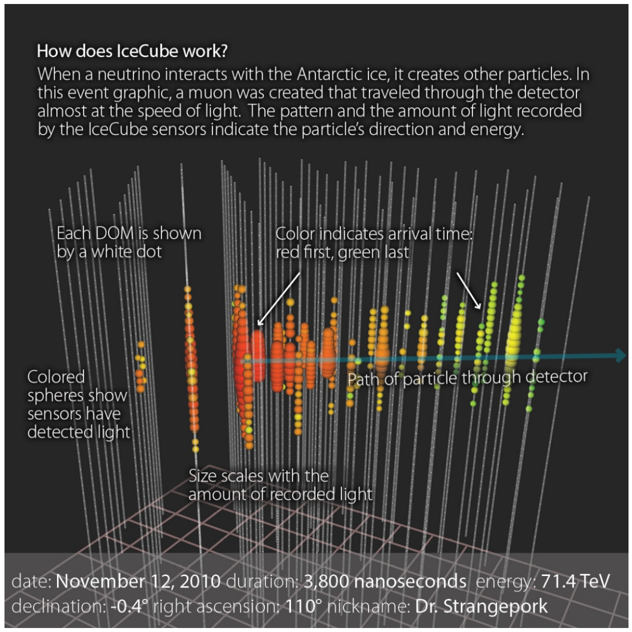

Figure 3: Structure of IceCube Observatory

used to point back to sources. Tau leptons create short-lived cascade events which cannot travel very far before decaying, and are usually indistinguishable from electron cascades. A tau could be distinguished from an electron with a "double bang" event, where a cascade is seen both at the tau creation and decay.

1.6 Atmospheric neutrino filtration

Cosmic rays impacting the Earth's atmosphere also produce muons. To filter out such muons, the IceCube detector considers the muons coming from the earth's crust, i.e, the muons that travel *upwards* while the atmospheric muons, which travel downwards are ignored.

However, some cosmic rays may pass through the earth's crust and cause upward muon noise. To distinguish these two types statistically, the direction and energy of the incoming neutrino is estimated from its collision by-products. Unexpected excesses in energy or excesses from a given spatial direction indicate an extraterrestrial source.

2 DATASET

2.1 IceCube

The IceCube public data release [1] includes occurrences found between April 2008 and July 2018 that are ongoing and just getting started. This catalogue comprises 1,134,450 neutrinos, with right ascension (RA), declination (δ), reconstructed muon energy and error in position, detector zenith, and azimuth angle provided for each neutrino. The median angular resolution is less than 1 degree.

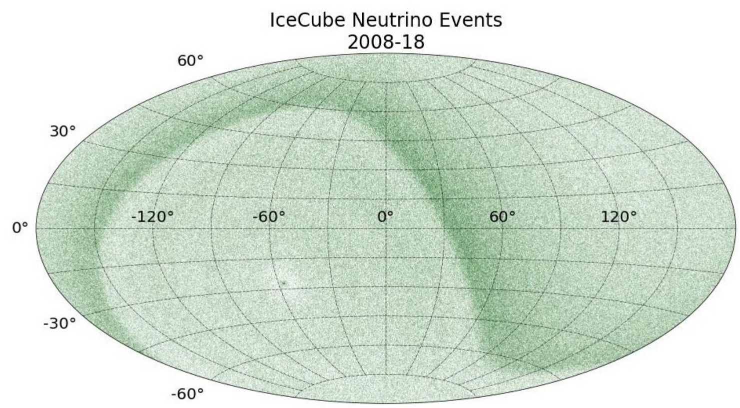

Figure 4: The darker regions indicate more density of events

2.2 Pulsars - ATNF

The pulsar dataset used in this project is from ATNF catalogue version 1.68, which currently includes 3341 pulsars [2]. We only needed the right ascension and declination of each pulsar for this project.

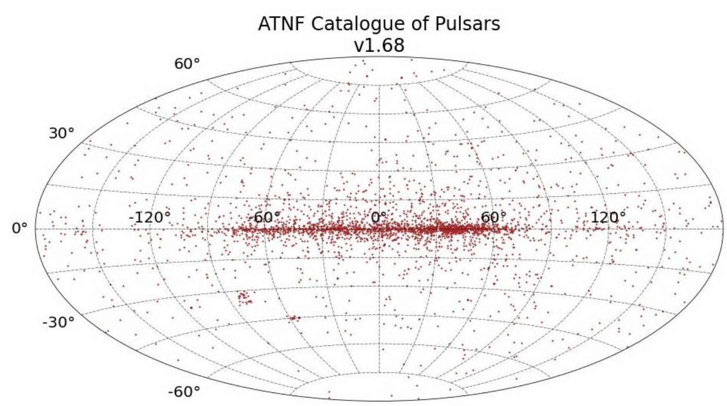

Figure 5

3 ANALYSIS

3.1 Pre-Processing

We chose neutrino occurrences with declination within 5° of the pulsar for our research. The majority of pulsars are found near the galactic plane. Because there are only two pulsars with > 85° (85.5° and 86.7°), we included neutrinos within 5° of the poles for completeness.

3.2 Maximum Likelihood Estimation

For this project, we used the unbinned maximum likelihood ratio estimation method as in [3, 4, 5, 6]. For a dataset of N events, if n_s signal events are attributed to a pulsar, the probability density of an individual event i is given by:

$$P_i = \frac{n_s}{N} S_i + (1 - \frac{n_s}{N}) B_i, \tag{1}$$

where S_i and B_i represent the signal and background pdfs, respectively.

The likelihood function ($\mathcal{L}$) of the entire dataset, obtained from the product of each individual PDF can be written as:

$$\mathcal{L}(n_s) = \prod_{i=1}^{N} P_i, \tag{2}$$

where P_i is the same as in Eq. 1.
The signal PDF is given by:

$$S_i = \frac{1}{2\pi\sigma_i^2} e^{-(|\theta_i - \theta_s|)^2 / 2\sigma_i^2} \tag{3}$$

where $|\theta_i - \theta_s|$ is the angular distance between the pulsar and the neutrino, whereas σ_i is the angular uncertainty in the neutrino position, expressed in radians.

The background PDF (B_i) is determined by the solid angle within δ of $\pm 5°$ around each pulsar ($\Omega_{\delta \pm 5°}$):

$$B_i = \frac{1}{\Omega_{\delta \pm 5°}} \tag{4}$$

3.3 Detection Statistic

The detection statistic (or the Z-score) used to ascertain the presence of a signal is given by:

$$TS(n_s) = 2 \log \frac{\mathcal{L}(n_s)}{\mathcal{L}(0)} \tag{5}$$

This test-statistic is the log-likelihood ratio of two hypotheses: H_1: Of all the N events, n_s are produced by the interested source.
H_0: All the N events are background events.

The likelihood ratio in Eq. 5 will indicate how likely it is that some of the neutrino events can be attributed to the interested source

3.4 Wilk's Theorem

Under the assumption of Null hypothesis (H_0) being true: When the sample size is very large, then the distribution of the test statistic TS approaches a χ^2 distribution[7].
The objective was to find $\hat{n_s}$ such that TS is *maximized*. If $\max TS(\hat{n_s})$ = 0, then the Null-Hypothesis is true, and the interested pulsar is not the source of the neutrinos observed in it's neighbourhood region of the sky.

4 RESULTS

4.1 Gaussian Fit

For each pulsar, we calculated the test-statistic TS and n_s for which TS is maximum. The detection significance is then given by $\sqrt{TS}$. The $\sqrt{TS}$ histogram is fitted to a Gaussian distribution, with the amplitude set at the ratio of the number of sources to the total number of bins per unit X-axis and the mean and standard deviation permitted to vary. Each bin's inaccuracy is equal to the square root of the total number of occurrences [4].

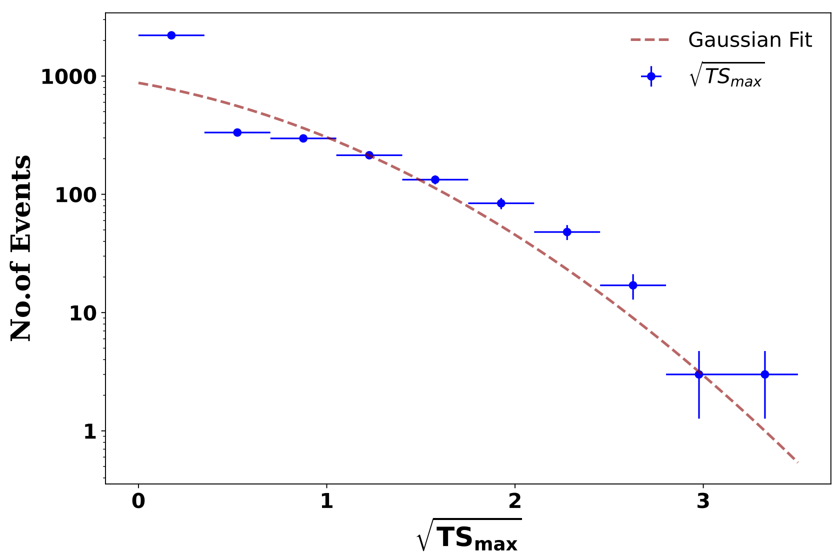

Figure 6: Histogram of distributions of $\sqrt{TS_{max}}$ along with error bars given by square root of the number of events. The dashed red line shows the best Gaussian fit to this data.

4.2 Inferences

From Fig. 6 we can observe that the Gaussian distribution does not match the data well since there is a slight excess of events with very low $\sqrt{TS_{max}}$ values in the first bin. In contrast to the background, we do not see a statistically significant excess. Since n_s is near to the physical boundary, the PDF of $TS(n_s)$ is a superposition of the χ^2 and δ function, which may also contribute to this excess [8].

The excess seen between 1.5 and 2.5 may be explained by errors in the PDF as well as by taking into account the trial factors[3].

Pulsar	$\tilde{n}_s$	$TS_{max}(\tilde{n}_s)$
J1849+0037g	43.5	12.3
J1707-4341	17.4	11.8
J1838-1849	16.5	10.4

Table 1: Pulsars with highest $TS_{max}(\tilde{n}_s)$ values

The distribution of occurrences with high significance as listed in (Table. 1) is consistent with background.Particularly the PSR B1509-58 which showed a 2.6σ excess, when combined with the Super-Kamiokande and MACRO results [9], has a TS_{max} = 0.

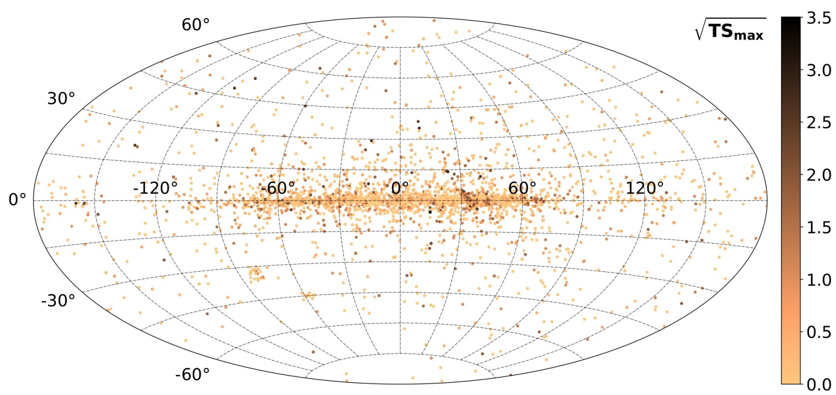

Figure 7: Skymap distribution of $\sqrt{TS_{max}}$ *in Galactic coordinates using Aitoff projection*

As a result, we draw the conclusion that *none* of the pulsars in the ATNF database at this time (on their own) are responsible for the diffuse neutrino flux seen by the IceCube.

5 SUMMARY/CONCLUSION

In this work we look for a spatially significant correlation between individual radio pulsars and TeV energy neutrinos. For our analysis, we used the publicly available IceCube neutrino catalogue, comprising 11,34,450 neutrino events observed between 2008-2018, and all the 3341 radio pulsars compiled in the latest version of the ATNF catalog. The analysis was done using the unbinned maximum likelihood ratio method. The distribution of the detection significance for each of the pulsars is shown in Fig. 6 and the skymap distribution in galactic coordinates in Fig. 7. A modest excess of events are seen in the first bin when the detection significance histogram is fitted to a Gaussian distribution. The occurences with high significance are consistent with the background. As a result, we can conclude that it is impossible for any of the known pulsars to be the source of the TeV-energy high energy neutrinos seen in IceCube.

ACKNOWLEDGMENTS

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I am extremely grateful to Prof. Shantanu Desai for guiding me through this entire project.

New things learnt

1. Learnt how neutrinos are produced and detected.
2. Learnt about likelihoods, maximum likelihood estimations.
3. Read various literature on IceCube, Neutrinos and likelihood analysis.
4. Learnt to use Linux, terminal/command-line, Git-GitHub.
5. Improved coding with python and learnt to apply various python libraries (numpy, numba, multiprocessing, etc) to parallelize the code execution and shorten the compile time.

In a future work, we will include a stacked contribution from all the pulsars

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