Sourcing Neutrinos to Their Corresponding Blazars

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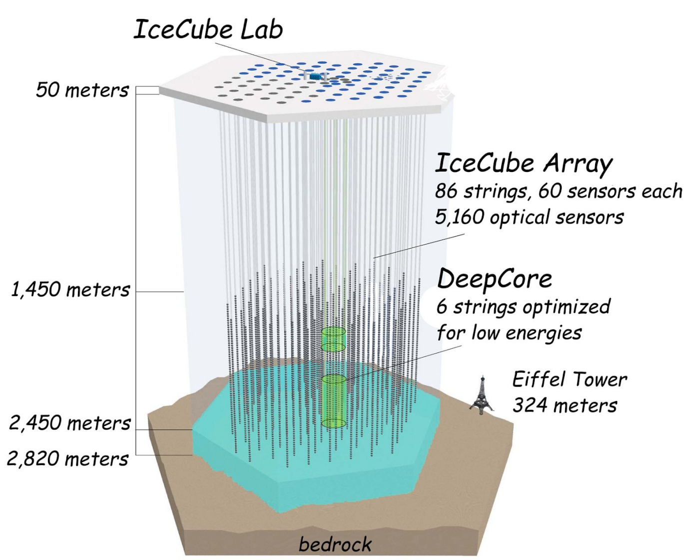
Abstract

Instead of observing with light, which twenty percent of the Universe is opaque to, scientists are starting to observe astronomical phenomena with neutrinos. Neutrinos are elusive particles. They have no charge, are nearly massless, and travel close to the speed of light. This makes them excellent messengers from places that are blocked from the electromagnetic spectrum, such as far-away supernovae and black holes. The purpose of this project is to create a software program that can match detected neutrino events to catalogued blazars, allowing scientists to determine if a neutrino from an undiscovered blazar was detected at any given time. Data was first scraped from an existing catalogue of blazars with the Selenium, requests, and BeautifulSoup modules in Python. After distances to the blazars were calculated, 3D polar coordinates and vector geometry was applied to determine which blazars were closest to neutrinos. This program was tested with verified data from IceCube Neutrino Observatory. This includes the neutrino event data that led to the discovery of the flaring blazar TXS 0506-056.This project achieved its purpose in matching a neutrino's event to previously known blazars that are closest by distance and angular difference. In the future, this may speed up the way by which blazars are identified by neutrino events in real time.



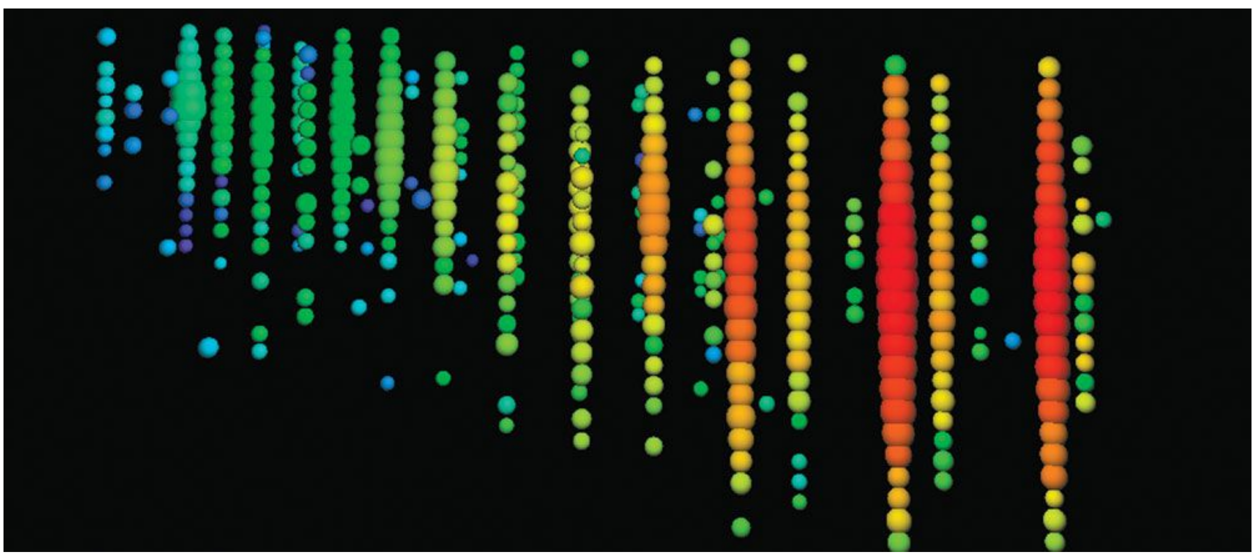
BACKGROUND

It has recently been theorized and proven experimentally that high-energy astrophysical neutrinos originate from blazars[1][5], a special type of quasar. Quasars (Quasi-stellar radio sources) are known to originate from supermassive black holes in the centers of galaxies and are the most luminous objects in the universe[3]. Surrounding these black holes are accretion disks, consisting of gas and other stellar material. When the black hole starts to consume the matter, the accretion disk experiences huge amounts of gravitational stress and friction, causing it to heat up to extreme temperatures[7]. This leads to the emission of the bright light and high energy particles from we call a quasar. Blazars are simply quasars that point directly at Earth. Scientists are still unsure about what exactly happens to the black hole or what nuclear processes the quasar undergoes to produce these particles at such high energies. By understanding the inner workings of quasars and how they affect their host galaxies, scientists will be able to further understand supermassive black holes.

Because the particles in accretion disks around blazars are so dense and energetic, light traveling from the blazar can be disturbed or even blocked by them. Furthermore, when scientists try to observe light coming from blazars, much of the electromagnetic spectrum is not able to travel the far distances without being distorted by giant gas clouds, or nebula. Therefore, scientists have searched for other methods of observing not only blazars, but other extragalactic phenomenon by means of neutrinos. Neutrinos are fundamental particles, part of a group of six fundamental particles called leptons. Three of the leptons, the electron, muon, and tau, all have a charge of -1 and vary in mass, while all the neutrinos, as their name implies, have no charge[4]. Most of the ones that we receive on Earth come from the fusion process in the Sun's Core. Yet, others can carry even greater energy, thousands of times more energy than those formed in the Large Hadron Collider. Astronomers believe that these high-energy neutrinos originate from sources outside of our solar system. Neutrinos, with their properties of no charge and almost no mass, travel close to the speed of light, so they pass through nearly everything quite easily, making them excellent messengers of far away sources. However, because neutrinos are so elusive, they are also very difficult for astronomers to detect.

Though hard to detect, neutrinos aren't always invisible. On the rare occasion when neutrinos bump into atomic nuclei and interact via the weak force, the collision creates electrons, muons, or tauons. These particles create a cone of blue light, called Cherenkov radiation, which is then detected by the detectors nearby. Similar to how a jet emits a sonic boom, neutrinos sometimes can go faster than light when in a certain media, such as water. The IceCube Neutrino Observatory in Antarctica has built one such detector made out of a cubic kilometer of pure transparent ice. Using more than 5,000 Digital Optical Modules (DOMs), researchers are able to detect the Cherenkov radiation trails emitted by the products of high-energy neutrino interactions, which can traverse the ice in any direction. In September 2017, IceCube observed an extremely high-energy neutrino event that coincided in direction and time with a blazar (TXS 0506+056) which was flaring at that time. They then further investigated neutrino event history back to 2008 and found that blazars are identifiable sources of high-energy astronomical neutrinos[5]. However, because blazar TXS 0506+056 was not visible at the time, scientists did not think of trying to match the neutrino event to the blazar in the past.

In the context of astronomy, time is very important. Currently, IceCube has developed an alert system that sends messages to telescopes all around the globe, ranging in spectrum from radio to gamma. However, telescopes may take time to slew to a certain point in the sky. By the time the telescopes are all pointed at the designated location, the event may have already ended, leaving no evidence for researchers. This program will allow neutrino astronomers to see whether or not a neutrino event is related to a blazar, even when the blazar is not visible at that moment. Moreover, this program should allow researchers in multiple neutrino observatories to efficiently analyze neutrino data, analyzing whether an event is likely to have come from a Blazar.



RESEARCH QUESTION

Is it possible to make an efficient program that finds blazars in the proximity of a high energy neutrino event?

HYPOTHESIS

By using Python and its modules along with 3D polar coordinates and vectors, it is possible to make a program that accurately chooses the nearest blazar to a given neutrino event.

METHODOLOGY

Data from the ROMA BZCAT blazar catalog was scraped with the Selenium, Requests, and BeautifulSoup modules in Python using Javascript commands. For example, to retrieve right ascension in degrees instead of hours, minutes, and seconds, setHead(Head, 1, 2) was called to select the right data format. The scraped catalogue recorded the name, right ascension in degrees, declination in degrees, and redshift (z) of each blazar in a JSON file format. All measurements used the J2000 reference epoch.

The first method of matching blazars to neutrinos was finding the actual distance between the neutrinos and blazars. To do this, the blazars and neutrinos were set to vectors, each with a direction and a magnitude. To approximately calculate the distances, or magnitude of the blazars from the Earth using their given redshift (z), Hubble's law was applied. Because the velocity that an object is receding from us is proportional to how redshifted it is, the velocity can be computed by multiplying the redshift (z) by the speed of light. Afterward, the distance can be found by dividing the speed by hubble's constant, 70. However, because some blazars' redshift (z) were 0, those data points were omitted from comparison. Moreover, because Hubble's law is quite inaccurate at small distances, a limit of $z > 0.25$ was also programmed to omit those blazars with redshift (z) smaller than 0.25.

After all the magnitude calculations were done, the polar coordinates were then converted into cartesian coordinates to find the direction components of the blazar. For polar coordinates, the declination of each blazar and neutrino was mapped from a range of [90, -90] to [0, 180], with declination of +90 being 0 degrees and declination -90 being 180 degrees. This new declination was set to a variable α to avoid confusion. θ was set to the right ascension. To find the cartesian coordinates of the blazar's position vector, the following equations were used:

$$x = r * \sin(\alpha) * \cos(\theta)$$
$$y = r * \sin(\alpha) * \sin(\theta)$$
$$z = r * \cos(\alpha)$$

Where r is the magnitude of each vector.

After finding the magnitude of the blazar vector and its components, the next step was to project it onto a neutrino vector, which would then allow us to find the distance between the blazars and the neutrino. To project the blazar vector onto a neutrino vector, the neutrino vector's magnitude is not needed. Therefore, the magnitude was set to one, and all previous steps to finding the blazar directional components were repeated and applied to the neutrino vector.

Finally, the projection vector was found by taking the dot product (the sum of the pairwise products of the components) of the neutrino vector and blazar vector. Using the Pythagorean theorem, the actual distance between the neutrino vector and blazar was calculated with the following formula:

$$d = \sqrt{|\vec{b}|^2 + |Proj_{\vec{n}}\,\vec{b}|^2}$$

Where $|\vec{b}|$ is the magnitude of the blazar vector and is the magnitude of the projection of the blazar vector onto the neutrino vector.

Another method of comparison was to compare blazars using their angular distance. The reason for this method was that the previously mentioned method relied heavily on the distance between the blazar and the Earth. However, as previously mentioned, certain blazars did not have redshifts given in the catalogue or the redshifts were just too small. Thus, there was a need for another method.

To find the difference in angles:

$$\Delta\alpha = \alpha_n - \alpha_b$$
$$\Delta\theta = \theta_n - \theta_b$$

Where α_n is the alpha of the neutrino, α_b is the alpha of the blazar, θ_n is the theta of the neutrino, and θ_b is the theta of the blazar.

Using the Pythagorean theorem, we can calculate the total difference in angle (*Δß)*:

$$\Delta\beta = \sqrt{\Delta\alpha^2 + \Delta\theta^2}$$

The program outputs 3 different result categories: the 10 closest blazars from the angular comparison method, the 10 closest blazars from the vector comparison method, and any blazars in common.

To test our program, public data was used from the IceCube Neutrino Observatory website. Specifically, this program was inputted with neutrino events that were thought to originate from blazar TXS 0506+056, starting from 2008 to 2017. A separate program was made to parse the neutrino event logs and run the main function on each neutrino event coordinate. This program also kept a log of how many times a certain blazar was closest in angular difference or actual distance.

RESULTS

After running through 1257 neutrino events that lead to the discovery of the TXS 0506+056 blazar, the program did very well in matching the correct blazar to the event. All three of the below graphs show the amount of times that our program returned a certain blazar first given a neutrino event. In other words, the returned blazar was closest to the neutrino by the method in its category.

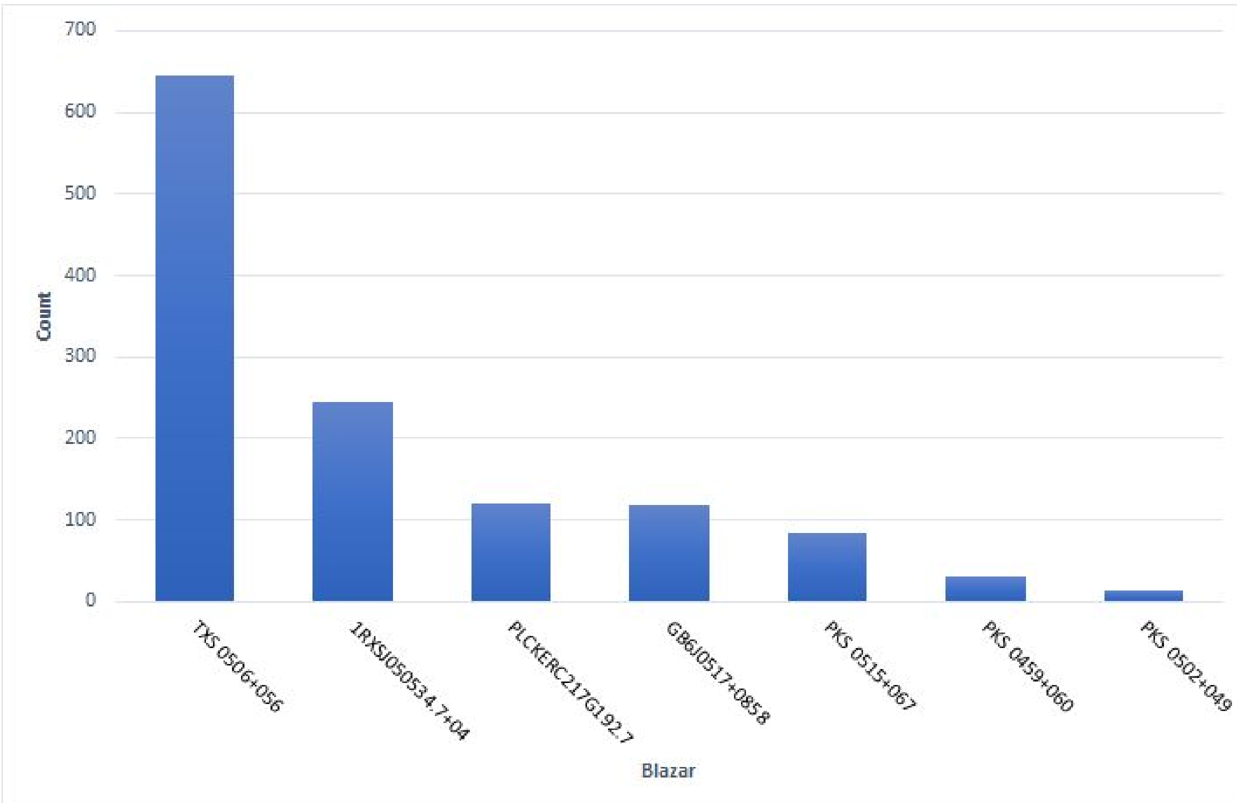


Figure 1.1

Figure 1.1 shows TXS 0506+056 as the clear candidate to focus on. By distance, blazar TXS 0506+056 was the closest the majority of the time, which would have made it an obvious blazar to observe as soon as possible.

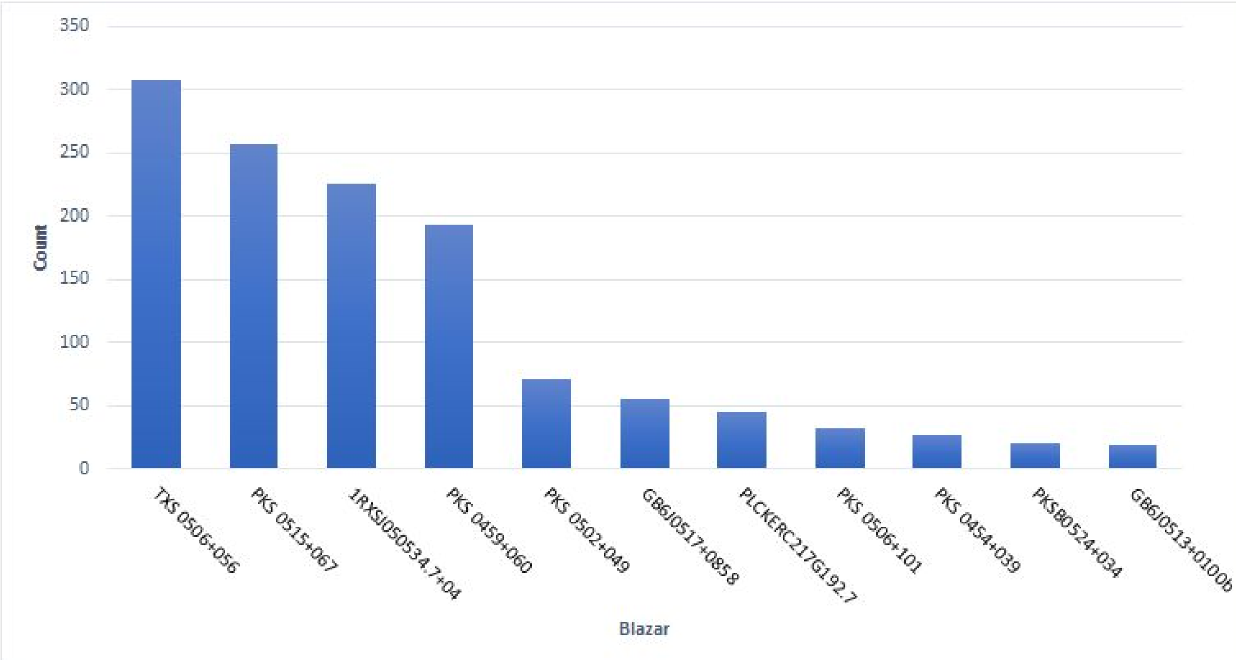


Figure 1.2

On the other hand, in Figure 1.2 blazar TXS 0506+056, though having the highest count, is not a winner of the majority by any means. The three blazars after it were counted frequently as well, meaning that the spread of the neutrino events may be too wide to narrow down TXS 0506+056 as the blazar to focus on. The increase in different blazars also shows the wider spread of data.

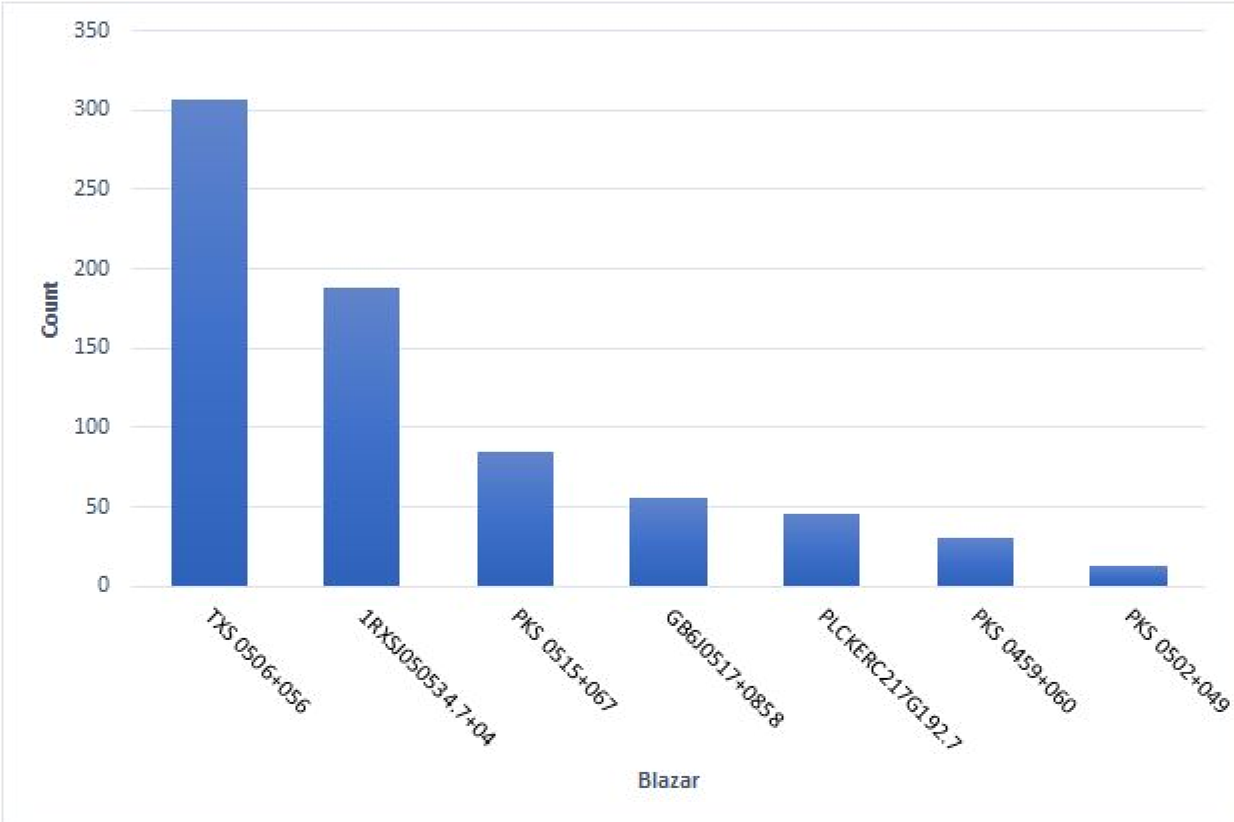


Figure 1.3

In Figure 1.3, the TXS 0506+056 is still the most commonly returned blazar. This graph measures how often a blazar was returned as the closest given the event coordinates of the neutrino.

DISCUSSION AND ANALYSIS

Based on the results, the hypothesis was supported. When the program was given a large set of neutrino event data, it was able to quickly determine the correct blazar it originated from (TXS 0506+56), as shown in Figures 1.1, 1.2, and 1.3. Though the graphs did not explicitly show it, it can also be inferred from the results that the program can accurately determine angular differences and distances apart of a neutrino and a list of blazars. However, in Figure 1.2, blazar TXS 0506+056 is only the closest in angular difference 1 out of every 4 neutrino. This implies that either the given set of data had a wide spread in right ascension and declination, or our method of finding angular difference was invalid.

Using this program, scientists will be able to collect clusters of neutrino events that seem to have come from a single blazar and observe whether the cluster truly originated from a blazar. As the program may get more efficient through multithreading and algorithmic improvements, the energy threshold for neutrino "alerts" will get lower and lower, until thousands of live neutrino events can be processed at once. Furthermore, users will be able to enter in a restriction on the angular distance, neutrino-to-blazar distance, or both to determine whether their set of neutrino events possibly came from an undiscovered blazar or not.

STUDY LIMITATIONS AND FUTURE DIRECTIONS

There are many factors in this study that may cause inaccurate data. One major aspect is the method of calculating the distance a blazar is from the Earth using a blazar's redshift (z) value. Not only is this a rough way of finding astronomical distances, but also there were many blazars that simply had z values of 0. Because of this, around one-sixth of the blazar data had to be skipped when trying to find distances. However, our second method of matching blazars to neutrinos using angular difference attempted to compensate for those blazars that were skipped previously. Because angular difference does not require any distances to be known, all blazars were able to be run through this method of matching.

Future studies may want to try to achieve a more accurate method of determining both distance and angular difference. It would greatly benefit future studies if blazar catalogs could increase the accuracy of redshift (z) to five or more significant figures. Furthermore, when neutrino astronomy becomes more mainstream, future studies can apply this program to other high-energy astronomical phenomena such as supernovae and neutron stars. These may also be possible sources of high energy neutrinos and should certainly be further researched.

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