An All-Sky Survey of Efficient Particle Accelerators

Introduction

Supermassive black holes occupy the center of every galaxy in the Universe. When these black holes are in the process of accreting matter around them, they are considered **active galactic nuclei (AGN)**. Approximately 10% of all AGN are capable of launching a collimated stream of matter via magnetic fields, which consists of particles that are accelerated close to the speed of light and can travel for thousands of light years (Brunner et al. 2022). This phenomenon is dubbed a **relativistic jet**. These jets emit energies across the electromagnetic spectrum, and the most powerful ones are capable of producing gamma-ray energies up to tera-electron volt (TeV) levels.

While there are various theories detailing the origin of these jets, there is no concrete understanding of the mechanisms that fuel this extreme particle acceleration. I hypothesize that these mechanisms will be most prevalent in the jets that are capable of TeV emission, the most energetic type of gamma-ray radiation. Therefore, by understanding TeV-emitting jets, a broader understanding of all relativistic jets can be obtained. Their physiology, their connection to the AGN's evolution, and their role in the development of the Universe are all mysteries to be solved.

To do so, I aim to produce a survey that spans most of the observable sky for TeV-emitting AGN in the hopes of understanding their relativistic jets. However, while there are a variety of telescopes that have scanned the sky in various wavelengths, there are none that have done so in the TeV energy range. To address this, I utilized the technique performed in a study by Massaro et al. (2013) that involves cross-correlating infrared (IR) and X-ray data taken across the entire sky. I obtained this data from the 'Wide field Infrared Survey Explorer' (WISE) satellite and the 'extended ROentgen Survey with an Imaging Telescope Array' (eROSITA) satellite at IR and X-ray wavelengths, respectively. Both surveys are the most recent in their respective waveband; in fact, the eROSITA data has yet to be released. Massaro et al. (2013)'s previous study in search of TeV-emitting jets utilized eROSITA's predecessor, 'ROentgenSATellit' (ROSAT). However, eROSITA observes a broader energy range from 0.2 to 8 keV, while ROSAT was only capable of detecting X-rays in the range 0.1 to 2 keV. Therefore, the new data collected by eROSITA holds great potential for my research regarding the discovery of new TeV-emitting AGN that have been missed by Massaro et al. (2013). As the eROSITA data release is planned for January 31, 2024, I have not yet had access to the full survey data. However, data for a smaller region of the sky called the 'eROSITA Final Equatorial Depth Survey' (eFEDS) has already been released. I have utilized it to prepare my search algorithm for new TeV-emitting AGN candidates. Therefore, the algorithm that is detailed in this paper has been tested on the eFEDS catalog and will be implemented once the eROSITA data release occurs.

Procedure & Results

I began by trimming down the IR data. The WISE catalog contains over 747 million sources, but by searching for objects with IR emission that is characteristic of relativistic jets produced by AGN, I was able to identify 131,021 matches. This was done by examining the slope of the IR spectrum peak of the AGN. This procedure was derived by Massaro et al. (2012) and utilized by Massaro et al. (2013).

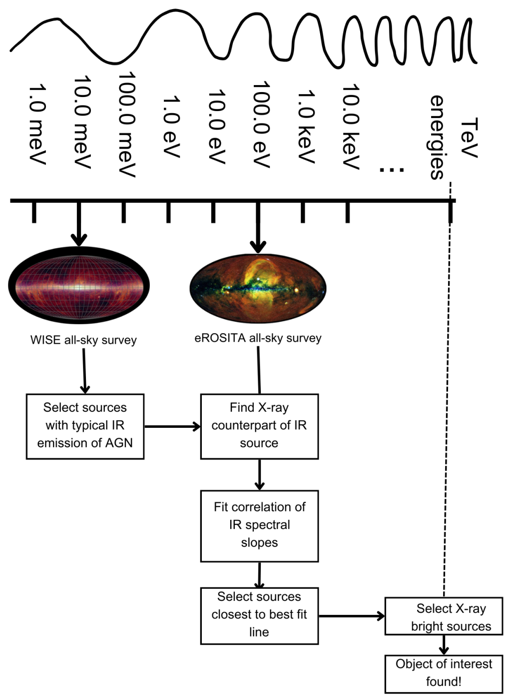

Figure 1: Flow chart depicting the procedure that was utilized in this study

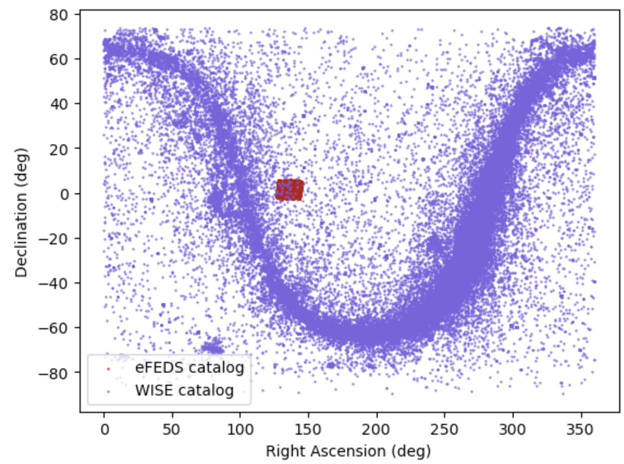

Figure 2: All-sky map of the sky in ecliptic coordinates, showing the reduced WISE field plotted in purple alongside the 140 square degrees of the eFEDS field (plotted in red). Note that the dense region of WISE sources represents the galactic plane, but as this graph is not shown in galactic coordinates, the plane is not linear.

Using the reduced WISE catalog as seen in Fig. 2, I matched the IR and X-ray data sets. Data points between the two catalogs were considered to be a match when the position in the sky at which they resided was the same, within a margin of error. Unfortunately, due to the small region covered by the eFEDS catalog, especially compared to the WISE catalog which includes sources across the entire sky, only 33 WISE sources fell within the eFEDS region, and only one match was found. As a result, further steps of the algorithm that involved comparing all candidate sources could not be performed. Instead, I investigated the X-ray flux of the single match to determine whether it is probable that this source could be emitting high-energy gamma rays. However, with an X-ray flux of $F_{X-ray} = (1.8 \pm 0.4) \times 10^{-14}$ erg/cm^2/s, it is not a good TeV candidate as the extrapolated gamma-ray flux from the X-ray emission is below the detection limit of current and future gamma-ray telescopes.

Utilizing the ROSAT data

Given that enough sources were not found in the eFEDS field to adequately test the algorithm, I turned to the ROSAT data that Massaro et al. (2013) utilized to evaluate the functionality and correctness of the algorithm. A newer version of the WISE catalog was released after 2013 (the publication year of Massaro et al. (2013)). As such, I expect not to reproduce the Massaro et al. (2013) results up to 100%, as my sample may contain a few additional sources.

I repeated the steps outlined above and found 182 matches between the ROSAT and WISE catalogs. Next, I computed the IR spectral slopes which can be seen as a comparison of the intensity of emission at two different wavelengths, using three wavebands ($12\mu m, 4.6\mu m,$ and $3.4\mu m$). For each source in the sample, the relation of the two different slopes ($4.6\mu m - 12.\mu m$ and $3.4\mu m - 4.6\mu m$) is compared and shown in Fig. 3. Using a linear regression fit, I selected sources for which the slope of the IR

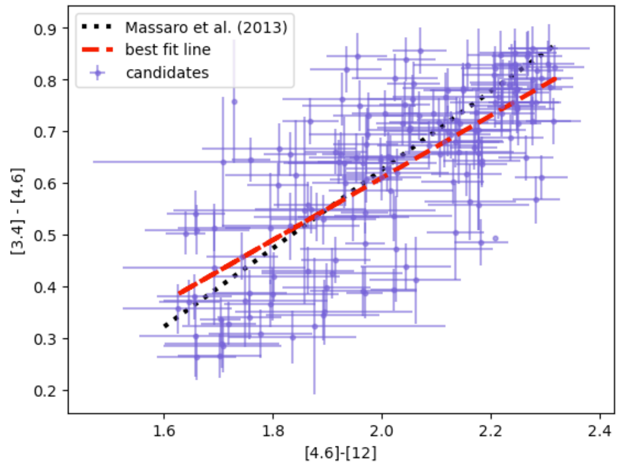

Figure 3: 157 TeV-emission candidates found by using the ROSAT and WISE catalogs. My best-fit line is shown in red. The best-fit line from Massaro et al. (2013)is plotted for comparison (dashed line).

was equal in both directions of change, indicating that the IR emission was constant. After selecting the sources that were closest to the best-fit line, I found 157 candidates for TeV emission.

Of these 157 candidates, 139 of them were found to exhibit an X-ray flux above the threshold, which marks likely candidates able to produce observable TeV-gamma-ray emission. In addition, as this X-ray and IR data has been available for quite some time, these 139 sources have been extensively studied in multiple wavelengths. I utilized this multi-wavelength data to confirm that my algorithm was detecting AGN capable of TeV emission. An overview of the algorithm can be seen in Fig. 1.

Conclusion

Despite the lack of data from the eFEDS-WISE comparison, the algorithm shows promise. Given the small size of the eFEDS catalog, it is not surprising that WISE has only observed one source in that region. Using ROSAT data, the algorithm shows very similar results to those of Massaro et al. (2013), as seen from the closeness of the best-fit lines in Figure 2. Overall, this algorithm displays the ability to handle an enormous number of objects (cf. 747 million sources in the WISE catalog), cross-match them with another large data set ($\sim$ 18,000 objects in the ROSAT catalog), and, based on information from only two wavebands of the electromagnetic spectrum, identify a precise number of active galaxies which are able to launch jets capable of efficiently accelerating particles to the highest energies.

Future Studies

The algorithm will be applied to the eROSITA data to be released in January 2024. I will be able to immediately analyze the data and efficiently produce a list of TeV candidates. I intend to compile a list of the most promising candidates (X-ray bright sources) which will be published in a peer-reviewed journal and can serve as a target list for future gamma-ray observatories, such as the Cherenkov Telescope Array. By making this list public, I will be able to give scientists within the community a list of target objects that can be studied as examples of efficient particle acceleration and will aid in the discovery of the mechanisms that power relativistic jets.

References

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