Building a Catalog of AGN with Erroneous Proper Motions and Parallaxes Using WISE and *Gaia*

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ABSTRACT

Context. *Gaia* is a very precise astrometric and photometric survey mission which has amassed data on millions of objects across the sky. Some of the objects are Active Galactic Nuclei (AGN) for which *Gaia* has incorrectly determined a significant parallax or proper motion. These determinations are known to be incorrect due to the vast distances at which these AGN are found.
Aims. We aim to construct a catalog of these incorrectly measured AGN in order to provide a new resource for locating interesting or unusual AGN. We also aim to characterize these AGN based on their surrounding environments and their optical characteristics.
Methods. We will identify several AGN candidates using the WISE catalog and then cross-reference these with *Gaia* to confirm measurements of parallax or proper motion. AGN with parallax or proper motion measurements having signal to noise ratios greater than three will then be studied visually using sky survey catalogs to determine which factors could lead to significant measurements of parallax or proper motion.

1. Background

In order to determine properties of celestial objects such as mass and luminosity, astronomers need to determine the distances to those objects. Astrometry characterizes the motions of objects in space, like parallax and proper motion, from which distances can be derived.[1]

Parallax is the apparent shift in position of an object due to the motion of an observer. As Earth revolves around the Sun, astronomers can look at the same object in space at 6-month intervals and measure, in arcseconds, the positional shift of that object in the sky. Parallax angles for even the closest stars are measured in**** fractions of an arcsecond which is why the best parallax measurements are taken by high precision telescopes located outside of Earth's atmosphere.[2] Knowing the parallax angle, astronomers can use trigonometry to calculate the star's distance. See Figure 1.

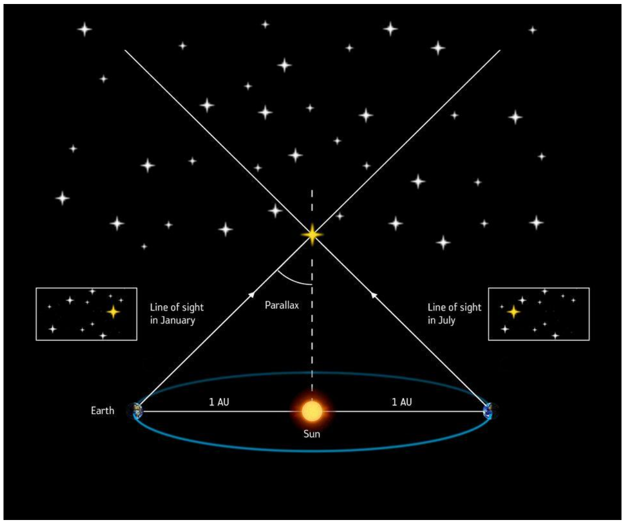

Figure 1. The yellow star is exhibiting parallax from the perspective of an Earth-based observer as seen in the two inset images. Using trigonometry, the observer can calculate the distance to the star using the Earth-Sun distance and the parallax angle.[1]

Parallax measurements show *apparent* motion of stars and other celestial objects but do not reveal the *actual* motion these objects exhibit across the sky. Radial motion along an observer's line of sight can be measured spectroscopically using Doppler shifting; however, transverse motion, called proper motion, is measured astrometrically. Proper motion is measured as an angular shift in position on the celestial sphere. The geometry for this is shown in Figure 2. As distance to a celestial object grows, the measured parallax and proper motion will decrease; consequently, faraway galaxies will be fixed on the celestial sphere due to their distances from Earth, and should therefore display no proper motion or parallax.[4]

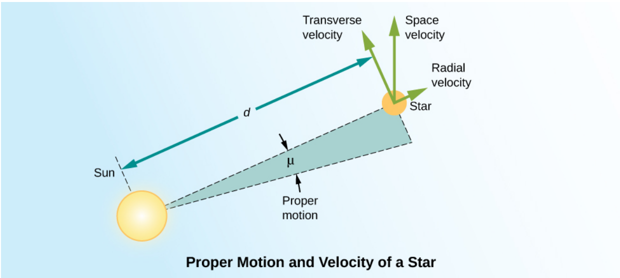

Figure 2. A star's proper motion is measured as the angular change in position on the celestial sphere over time.[3]

Gaia is a European Space Agency mission that is currently developing the largest and most precise three-dimensional map of our galaxy. It will determine the proper motion, parallax, and position of the largest sample of celestial bodies to date. Interestingly, analysis of *Gaia*'s proper motion and parallax measurements yield some unexpected results where known quasars have measurable proper motions.[4] Quasars are the most luminous active galactic nuclei (AGN) which are the cores of galaxies where supermassive black holes are found. The AGN light is a result of accretion of gas onto the

[1] https://www.esa.int/Science_Exploration/Space_Science/Gaia/How_does_Gaia_study_the_Milky_Way

supermassive black hole. Observed data for known quasars suggest that they are at least 600 million light years away with most being billions of light years away.[6] And so AGN can often appear as point sources due to their extreme distances from Earth.[5] These *Gaia* results are unexpected since only objects within or very near to our galaxy (a few hundred thousand light years) should exhibit a measurable proper motion or parallax during the five year time frame of *Gaia*'s measurements.

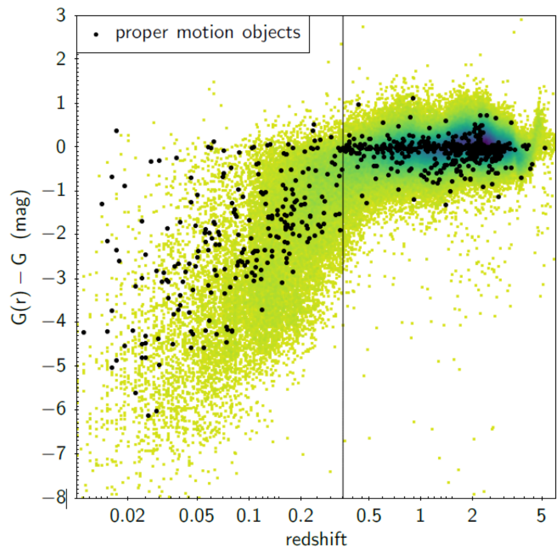

Figure 3. The plot above shows several objects with proper motion which are located at redshifts indicating a location outside of the Milky Way..[4]

Gaia DR3 has identified 6,649,162 quasars and of that sample Souchay et al. looked at a subsample of 416,113 objects in the Large Quasar Astrometric Catalogue-5 and identified 41 objects, which exhibited proper motion and are located outside of the Milky Way Galaxy (See Figure 3).[5,8] Due to the distance to these objects, these motions are not likely physical. A possible explanation for AGN with proper motions is simply that the *Gaia* pipeline is assigning incorrect interpretations to its observations. Since *Gaia* has cataloged more than 6 million quasars[9], even an error rate of 0.01% on proper motion observations could produce hundreds of AGNs with observation errors. If mechanical error or failure is causing *Gaia* to collect inaccurate observational data producing apparent proper motions in AGN, we would expect these errors not to be tied to specific attributes of AGN. However, if these measurements are accurate, they may be related to some physical attributes of these AGN. Some attributes which might be confusing *Gaia* are gravitational lensing along the line of sight to the quasar which results in multiple images, or possibly a binary AGN system.

The goal of this research project is to compile a list of AGN categorized as having significant proper motions or parallaxes and cross reference these sources to other AGN characteristics in order to draw conclusions as to what about these particular AGN misled the *Gaia* pipeline into reporting proper motions or parallaxes when none exist. This analysis may provide a new method by which this unusual subset of AGN could be identified.

2. Analysis

As pointed out in J. Souchay et al. 2022,[5] there are at least 41 sources known to be AGN for which large proper motions (>10 milli-arcseconds yr^{-1} with a signal to noise ratio of 3 or greater) have been measured. *Gaia* has recorded a much larger set of AGN than Souchay et al. examined which may also have proper motions or parallaxes of $S/N \geq 3$. We seek to characterize the intrinsic or environmental factors of the various AGN giving rise to the erroneous determinations of astrometric motion.

We will start with all sources in the Wide-field Infrared Survey Explorer (WISE) catalog which have been identified as AGN.[10] The WISE AGN catalog is the one of the largest in existence with 4,543,530 AGN with 90% reliability. These sources will be cross-referenced with *Gaia* data to determine which have nonzero parallax or proper motion values. An initial analysis of the data will look for proper motion/parallax values with a signal to noise ratio greater than or equal to 3 ($S/N \geq 3$); depending on the size of the resultant data set, the parameters may be adjusted to yield an appropriately-sized sample set for further evaluation (possibly an increase to a S/N ratio of 5 if the data set is still very large).

The catalog of objects that meet both cr-iteria outlined above (significant proper motion/parallax in *Gaia* for an object identified as an AGN in the WISE survey) will then be searched in other databases for optical images such as the SIMBAD Astronomical Database;[11] NASA Extragalactic Database (NED); the ESO Online Digitized Sky Survey; and the Sloan Digital Sky Survey.[12] The goal of this search will be to identify trends or commonalities in the collected objects that could help explain why *Gaia* attributes proper motion/parallax to these objects. Our analysis of the images from these surveys will attempt to ascertain the likelihood that apparent proper motions/parallaxes are the result of additional celestial objects within the line of sight of the AGN candidate. If this is the case, those AGN candidates with an apparent proper motion/parallax will be identified as being in a crowded field that may be confusing the *Gaia* measurements.

Additionally, we will include information on AGN type to see if they are correlated with the erroneous proper motions/parallax measurements. For example, if our sample of AGN is predominantly radio-loud, this may increase the likelihood of emission from astrophysical jets being the cause of confusion for the *Gaia* pipeline. Another possible source of confusion may be that these sources are gravitationally lensed. If our AGN candidates are gravitationally lensed, this could also lead to erroneous measurements of proper motion/parallax.

Finally, if after analyzing all these possibilities and we are left with AGN candidates with no identifiable explanation for the apparent proper motions/parallaxes, we will map these candidates out in the sky to see if any pattern in their location emerges. Such a pattern could imply a previously unidentified systematic instrumental anomaly in the *Gaia* survey. If our sample has randomly positioned AGN with apparent proper motions/parallaxes that show no other pattern, it would imply that the proper motion/parallax measurements are the product of random equipment or pipeline anomalies.

3. Conclusion

The goal of this research project is to compile a list of WISE-selected AGN which the *Gaia* DR3 has identified as having significant proper motions or parallaxes. We will cross-reference these sources with the SDSS, DSS, and various other databases to analyze characteristics observed in their environments or, otherwise, inherent to these sources. We will then draw conclusions about how these particular AGN misled the *Gaia* pipeline into reporting proper motions or parallaxes in an attempt to provide a new method of identifying this unusual subset of AGN.

4. References

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5. Outreach

Don Carpenetti
Develop and present outreach events based on the 2023 research project for general science audiences:

- Mad Scientist Camp and Jr. Mad Scientist Camp at Craven Community College
- Country Lakes Senior Living Community, Little River, SC, Summer 2024
- Summer program at Winterville Public Library, Winterville, NC

- Camps at St. James United Methodist, Greenville, NC, (likely to be 3 or 4 different groups of students spread across the summer)

Present on the NITARP program:

- Craven Weekly Podcast/Webcast, Spring or Summer 2024
- All available opportunities through NSTA Committee on Post-Secondary Education (I'm on the committee through June 2024)
- Craven Community College is planning an event for late summer 2024 for local (Craven county) middle and high school teachers with presentation about the NITARP program as the keynote address.
- Pitt County Schools high school science teachers

Combination events (science and promoting NITARP)

- Craven Community College Honors Program Showcases – Spring 2024 and Fall 2024 (participating students also likely to present)
- Craven Community College Faculty Showcase, Fall 2024
- Craven Community College Astronomy Club

Spencer Cody
Formal Presentations about NITARP:,

- Present on the NITARP program at the South Dakota STEM Ed Conference in Huron, South Dakota, in February of 2024
- Present on the NITARP program at the National NSTA Conference in March/April of 2024; location to be announced

Informal Presentations about NITARP:

- Will be networking with teachers at the NSTA National Conference in Atlanta promoting the program
- Will be networking with teachers at the South Dakota STEM Ed Conference in Huron promoting the program

NITARP Curriculum Development:

- Will be incorporating research information into our Earth Science curriculum focusing on galaxy formation
- Will be combining NITARP research information with our current NASA/SETI AAA learning modules for my Physical Science, Conceptual Physics, and Physics classes
- Will be encouraging more students to enter authentic research programs as a result of NITARP participation through the South Dakota School of Mines
- Currently offering NITARP research as a high school Astronomy credit course for this spring semester with two students enrolled

NITARP Promotional Development:

- Currently working with major news outlets to develop a story on our selected students to promote the NITARP program
- Will be distributing NITARP information about our school's experience through the South Dakota Science Education Listserv
- Will be distributing NITARP information about school's experience through the South Dakota DOE Facebook page and our school's Facebook page

Cea Fortarezzo

- Write a curriculum unit for a science elective course called "Introduction to Astronomy." The course will be targeted towards 11th and 12th grade students in the Philadelphia School District (PhilaSD). The unit will implement a hands-on focus to inspire student engagement and a sense of wonder about the cosmos. This curriculum will be designed with scaffolding of science concepts, and will provide extensive opportunities for accommodations to support a diverse group of learners.
- Lead a Professional Development seminar via PhilaSD, targeted towards high school teachers who might be interested in teaching the "Introduction to Astronomy" science elective course.
- Present NITARP Project to professional teaching organizations in the PA/NJ area such as PRISE (Philadelphia Regional Institute for STEM Educators).
- Encourage high school students in Philadelphia to pursue STEM careers. Highlight African American scientists and astronomers in the classroom.

David Friedlander-Holm

Presentations about NITARP program to whole school

- Fall 2023 (by students or me, probably me)
- Spring 2024 (by students or me)

Presentations about NITARP program to teachers at Bay:

- Teaching seminar for non-science teachers about data visualizations, methods of research and modes of collaboration
- Teaching seminar to science teachers on details of research methods and data accessibility

Students will be responsible for:

- Internal exhibition during at least one of the exhibition periods we have at our school
- Produce a short presentation using the AGNatha poster as individuals
- Responding to Likert scale surveys on an on-going basis

Outside school:

- Present to CATDC on methods and results
- Reach out to local astronomy clubs to share with them

Justin Hickey

Presentations about NITARP program/my experience:

- Episcopal High School Inservice Days, Aug 2023
- UT EXES Teacher Program Meeting, Spring 2024

Presentations w/ students about research:

- Arrange dates with local astronomy clubs
- EHS Admissions events, 2023-24 school year
- EHS Fundraising events, 2023-24 school year

Publications featuring our work:

- EHS Pillars magazine, Spring 2024
- Local community newspaper highlighting AAS experience, Spring 2024

Educational Initiatives:

- Use NITARP-style framework for student astronomy research as part of EHS's Independent Study program
- Introduce archival research into one-semester Astro 101-type elective course at EHS