Investigating Anomalies in Astrometry of AGNs in *Gaia* Data

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Abstract

Context. *Gaia* is an astrometric mission measuring the position of millions of objects in the sky. An active galactic nucleus (AGN) is one example of such objects, and some AGNs register as having parallax or proper motion. AGNs should not register parallax or proper motion as they are in other galaxies, and are therefore far too distant for us to detect their parallax or proper motion. The Wide-field Infrared Survey Explorer (WISE) is a mission that has repeatedly mapped the sky in infrared wavelengths, and cataloged three quarters of a billion objects, of which there are over 4 million AGNs, which allows us a much larger sample size than what *Gaia* has identified on its own. In 2023 a NASA/IPAC Teacher Archival Research Program (NITARP) team analyzed the WISE AGNs in *Gaia* so as to construct a catalog of the interesting and unusual AGNs with incorrectly measured parallaxes.

Aims. We will create a similar catalog for proper motion. Our team will analyze the proper motions of WISE identified AGNs for which there is astrometry from *Gaia.*The research will seek to identify a cause for the discrepancy between the astrometric measurements and identification as an AGN.

Methods. Our team will crossmatch identified AGNs from WISE with sources in *Gaia* Data Release 3 (DR3) that have proper motion. Once we have this larger catalog of anomalous targets, we will analyze it to see if there are other unique characteristics or environmental factors that they tend to share to gain insight as to why these anomalous readings are happening. This will include cross-referencing them with optical sky surveys.

1. Background

Astrometry is the precise measurement of astronomical objects by their position in the sky, and how those positions change over time. By looking at many objects relative to each other and taking multiple measurements over years, we can account for Earth's motion around the sun, and movement within our galaxy. Then, we can measure which objects are "fixed" background objects and which are closer objects whose relative apparent positions change, either due to proper motion or parallax.

Proper motion is an apparent change in position of an astronomical object due to that object actually moving through space laterally or vertically relative to our position (transverse motion) which is measured by its angular shift, in seconds of arc per year (Figure 1)(Seeds, M. & Backman, D. 2016, p. 178). Movement towards or away from us (radial motion) would instead be detected by its Doppler shift and is not included in a proper motion measurement. The further away an object is, the faster its transverse motion must be in order to have its proper motion detected by us over years or decades. Other limitations arise due to resolving power, or how well we can accurately distinguish between two very close points in the sky.

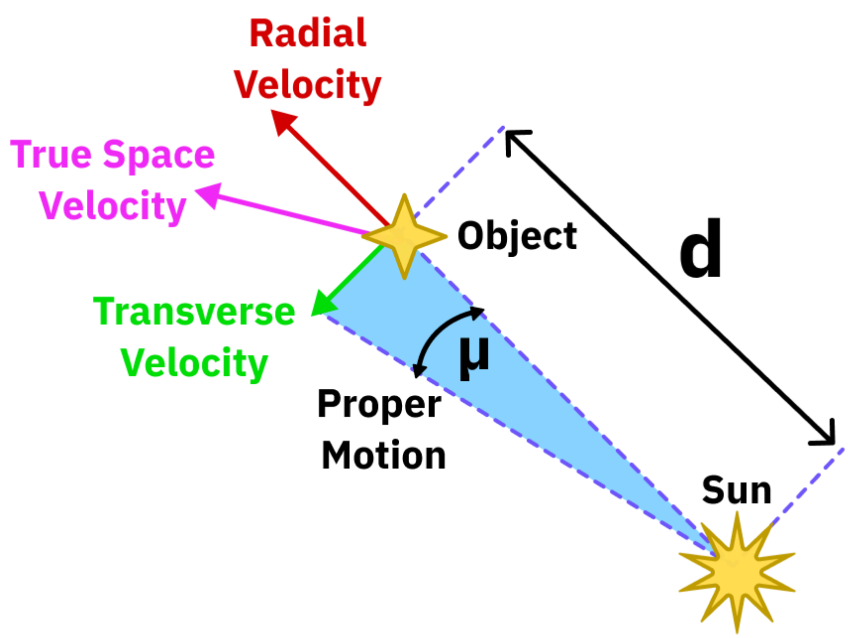

Figure 1: Diagram depicting how the true velocity through space of an object has both a radial and transverse component. Only the transverse portion registers as proper motion which can be measured as a change in apparent position relative to background objects. (Image: D. DeMatte, 2024)

Parallax measurements, however, quantify apparent motion of stars and other celestial objects due to the motion of the Earth in its orbit and their distance from Earth. They do not reveal the actual motion of these objects, but rather, through a periodic oscillation that matches our orbit, they can allow us to determine the distance to nearby objects in our own galaxy.

Launched by the European Space Agency (ESA), the *Gaia* mission is charting out the positions and motions of objects across the entire sky.[6] To date it has mapped 1.8 billion objects in the Milky Way galaxy and beyond. Specifically, *Gaia* has a one-billion-pixel camera that can provide improved measurements of parallax and proper motion by giving accurate position measurements for a star or another celestial object such as an active galactic nucleus (AGN).

AGNs are highly luminous cores of galaxies that outshine the stars in that galaxy. They are supermassive black holes interacting with matter nearby by pulling it into an accretion disk. They potentially fling matter away along jets (Figure 2). The accretion disk can emit incredible amounts of light that can be detected from our galaxy, but is distinguishable from stars due to differences in the color of light. Material flung away from the AGN in jets can interact with magnetic fields to produce synchrotron radiation, primarily emitting in the radio wavelengths. This means that AGNs can be distinguished from a star by a couple methods, including analyzing for color differences such as ultraviolet or infrared excess, or by looking for a strong radio signal (Peterson, B. M. 1997, p. 238).

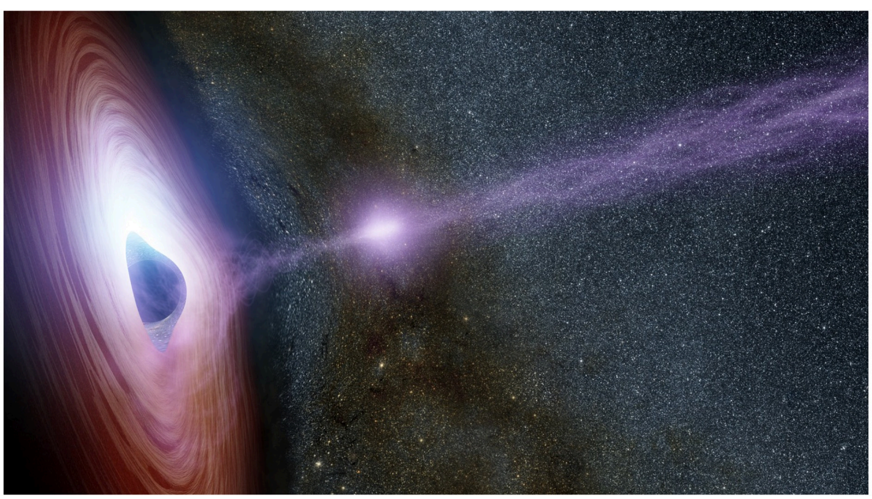

Figure 2: Artist's rendering of black hole with jet and accretion disk. (Image: R. Hurt (IPAC/Caltech))

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[6] *Gaia.* European Space Agency. https://www.esa.int/Science_Exploration/Space_Science/Gaia

AGNs range in distance from tens of millions of light years away like Seyfert galaxies to billions of light years from Earth in the case of quasars.[7] At these vast distances, AGNs should appear fixed and should not show any measurable parallax or proper motion. Souchay et al.(2022) compiled 416,113 AGNs from the Large Quasar Astrometric Catalog-5 (LQAC-5) that were also measured by *Gaia* Early Data Release 3 (EDR3). Of that sample, they identified forty-one AGNs as exhibiting proper motion. These objects are located outside of the Milky Way Galaxy, and while they likely have physical motion, observed motion is not likely (Figure 3). Thus, the *Gaia* results are unexpected as only objects within or very near to our galaxy (approximately ten thousand light years) should exhibit a measurable proper motion or parallax during the five year time frame of *Gaia*'s measurements.

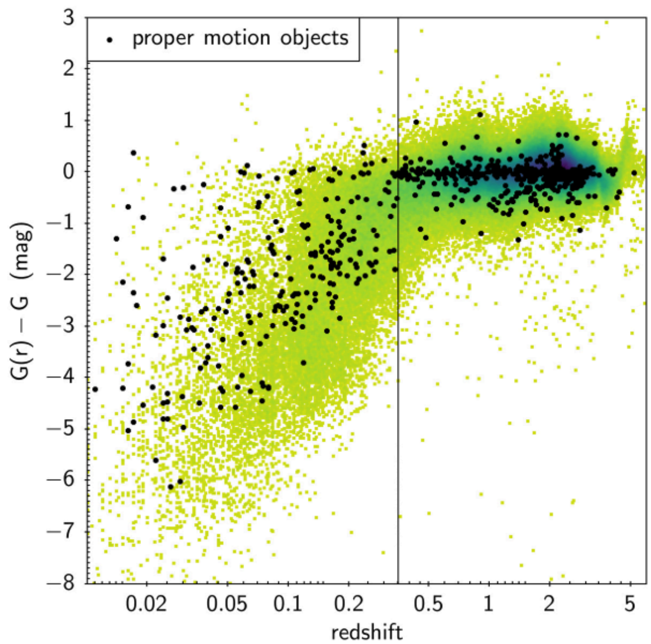

Figure 3: Total *Gaia* red (G(r)) filter - Gaia white light filter (G) colors vs redshift. This figure highlights how *Gaia* assigns proper motion values to AGNs (black dots) along a similar distribution that AGNs follow generally (green dots) across a range of distances (Souchay et al. 2022).

The Wide-field Infrared Survey Explorer (WISE) mission has repeatedly mapped the sky in the infrared part of the spectrum, and cataloged billions of objects.[8] In part because IR detection works even for AGNs that are obscured by dust surrounding their

[7]*What Are Active Galactic Nuclei?* Webb Space Telescope.
https://webbtelescope.org/contents/articles/what-are-active-galactic-nuclei/

[8]*Wide-Field Infrared Survey Explorer.* NASA Jet Propulsion Laboratory.
https://www.jpl.nasa.gov/missions/wide-field-infrared-survey-explorer-wise

accretion disks, WISE has one of the largest AGN catalogs to date. The R90 catalog consists of 4.5 million objects that Assef et al. (2018) have identified as potential AGNs, with 90% confidence. That allows us a much larger sample size than Souchay et al. (2022) where we hope the larger number of objects will reveal a pattern that will lead us to the origin of the erroneous proper motions.

A 2023 NITARP team investigated *Gaia* parallaxes attributed to AGNs, and found that 2,581 of those AGN candidates registered as having a parallax, with a signal-to-noise ratio of at least three, and 419 of those were spectroscopically verified as AGNs and visually inspected for confounding environmental factors (Carpenetti et al. 2024)(Figure 4). We aim to create a similar data set for proper motion.

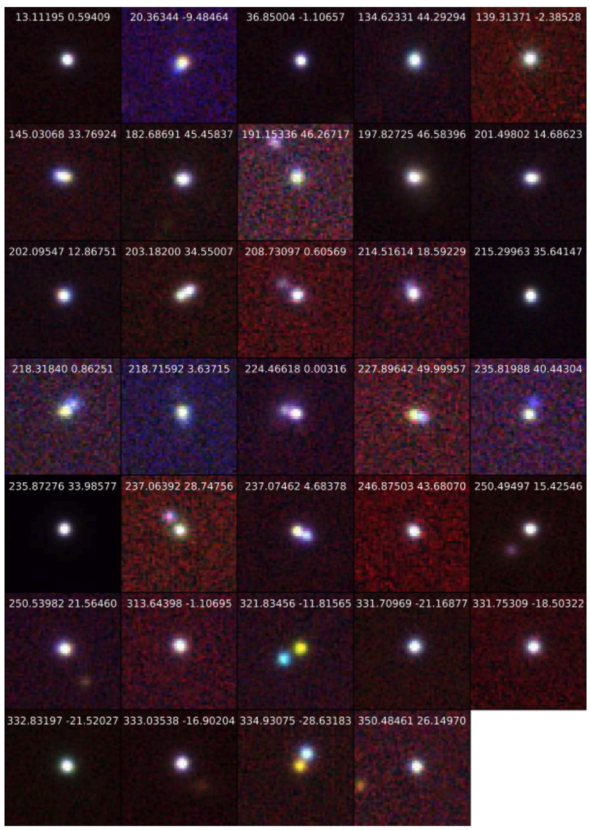

Figure 4: Pan-STARRS *giy* images of quasars exhibiting proper motion. 12”x12” cutouts of 34 final objects from Souchay et al. (2022) after visual inspection was completed, highlighting the potential impact of neighboring sources as a cause of error in astrometry.

Our goal is to compile a catalog of as many AGN candidates as possible that have proper motion in *Gaia* data release 3 (DR3), so that we can do statistical analysis in order to draw meaningful conclusions about why there are so many AGN candidates that are registering proper motion.

2. Analysis

The release of *Gaia* DR3 included the position in the sky, photometry, parallax, and proper motion of 1.8 billion objects (an increase of ~100 million sources over *Gaia* DR2) with a limiting magnitude of G = 20.7. Photometric measurements included over 1.8 billion sources in white light, 1.5 billion sources in blue light and more than 1.5 billion sources in red light.[9]

Souchay et al. (2022) matched 592,809 sources from the LQAC-5 AGN catalog with *Gaia* Early Data Release 3 (EDR3) which led to 416,113 cross matched celestial objects. Of these candidates, forty-one AGNs that have a large proper motion (h >10 $mas \cdot yr^{-1}$) were identified.

Our goal is to investigate a larger number of AGN candidates with significant proper motions to better understand why these objects are registering as AGNs with proper motion. We will start by retracing the steps of the previous NITARP group, starting with the WISE catalog of 4,543,530 AGN candidates with 90% confidence (R90, of which about 10% may be misidentified), and co-locate them in DR3. We will also check for any *Gaia*-identified AGN candidates that aren't represented in the R90 catalog. If there are any, we will keep them as their own data set for future comparison.

These data sets will be checked for AGNs that have significant proper motion in DR3. In order to reduce false positives due to noise in the astrometry, we will only consider targets with a signal-to-noise ratio of three or greater (S/N≥3). Our team will cross-analyze optical data from the Sloan Digital Sky Survey (SDSS), the Digitized Sky Survey (DSS), the NASA Extragalactic Database (NED), and search the SIMBAD astronomical database to visually inspect images in these databases and assist in potentially explaining why any AGN has a proper motion attributed to it in *Gaia* DR3. Finding celestial objects within the field of view of an AGN may contribute to confusion in *Gaia's* measurements. Lensed quasars may also lead to erroneous proper motion measurements confusing the *Gaia* pipeline, similar to nearby objects seen in Figure 4.

Our goal is to identify any objects misidentified as AGNs (i.e stars with unusual WISE colors similar to AGNs) as well as confounding circumstances causing *Gaia* to erroneously assign proper motion to AGNs.

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[9] *Gaia Data Release 3*. European Space Agency. https://www.cosmos.esa.int/web/gaia/dr3#

This refined data set will be analyzed for several potential correlations. We will check their position in the sky relative to the general population of AGN candidates. If the anomaly is arising from previously unknown issues with *Gaia* measurements in only a part of its orbit around the sun, these would show up in only parts of the sky. We would expect the anomalies to likely appear in clusters that are opposite from each other on the sky as *Gaia* determines its astrometry based on comparing opposing parts of the sky. Finally, we will cross reference with other databases (SDSS, SIMBAD), including in other wavelengths(i.e. x-ray, radio), to see if there are correlations with the type of AGN and the frequency with which it registers proper motion.

3. Conclusion

Once we have a reliable list of WISE-selected AGNs with a high signal-to-noise ratio for non-zero measurements of proper motion in the *Gaia* DR3 catalog, we will analyze them for spatial correlations that suggest a previously unnoticed systematic error in astrometry. Cross-referencing with SDSS and DSS will allow visual inspection of the sources to check for various confounding objects or environments (bright foreground stars, dense starfields, et cetera). We will also cross-reference with NED and SIMBAD to see if the identified sources belong to a particular AGN subtype (radio loud, lensed, et cetera). We will then draw conclusions about the source(s) or cause(s) of anomalous astrometry of high confidence AGN targets and how these particular AGNs misled the *Gaia* pipeline into reporting proper motions.

4. References

Assef, R. J., et al. 2018 "The WISE AGN Catalog" The Astrophysical Journal Supplement Series, Volume 234, Issue 2, article id. 23, p. 22

Carpenetti, D., et al. 2024, "Building a Catalog of AGN with Erroneous Parallaxes Using WISE and Gaia" (Pasadena, CA: IPAC/NITARP) https://nitarp.ipac.caltech.edu/system/media_files/binaries/265/original/carpenetti2024.pdf?1703385583

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Seeds, M. & Backman, D. 2016, *Foundations of Astronomy* (Enhanced Thirteenth Edition; Boston, MA, Cengage Learning)

Souchay, J., et al. 2022 “Quasars with Large Proper Motions: A Selection from the LQAC-5 Catalog Combined with Gaia EDR3-Focusing on Astrometric and Photometric Properties.” Astronomy & Astrophysics. 660: A16. 6.

5. Outreach

Develop and present outreach events based on 2024 research project:

David Forester:

- Creation of a research project activity for the high school level astronomy class at Mission Vista HS that will have students utilizing the IPAC database to investigate the answer to a question of their own asking by analyzing the archival data themselves.
- Presentation of information about IPAC in the astronomy class unit about telescopes and modern astronomy research at Mission Vista HS.
- Presentation to astronomy students at Mira Costa College about the results of this research, and sharing about IPAC generally.
- Outreach to the Southern California Desert Astronomy group about how to access and utilize IPAC database
- Potential outreach to San Diego Astronomy Association
- Collaboration with other astronomy teachers in Southern California

Benjamin Senson:

- Presentation on NITARP and the Cyclops AGN research project specifically at a meeting of the Madison Astronomical Society
- Create a planetarium program for presentation as one of the monthly public shows offered by the MMSD Planetarium that is focused on AGNs and integrates this research.
- Present to the Vel Phillips Memorial HS Astronomy Club regarding the research experience and the publicly available databases of astronomical observations that can support citizen/professional research.
- Integrate into Solar System Ambassador presentations (as appropriate)

Michelle Stella Riordan:

- Present at Police Activities League Egg Harbor Township & Atlantic County (PAL) Annual STEM Expo. Create a poster of my experience and how teachers may incorporate using real data into their classroom
- Present NITARP experience to New Jersey STEM Pathways Network and South Jersey STEM Network.
- Present research to PAL Stargazer group to gauge interest in research opportunities. Create a research project for middle and high school students incorporating real data.
- Present research to South Jersey Astronomy Club during our monthly zoom meeting.
- Present NITARP program to NASA Endeavor teachers. Create a slideshow of my experience and how other teachers may incorporate data into their astronomy classes
- Provide professional development for teachers through the New Jersey Education Association (NJEA) conference.

Lenee Mason:

- Engage in and facilitate professional development opportunities for in-service science teachers Suffolk County Board of Cooperative Educational Services (BOCES); a New York State public organization created by NY legislation which provides educational programs to children and adults.
- Speaking to pre-service science teachers at Molloy University as a NOYCE Ambassador Program alumni.
- Starting an Astronomy Club at Copiague Middle School where students will learn skills and concepts that were acquired while being a part of NITARP. Students can participate in their own research and build their interest in astronomy. Potentially find local observatories and science programs to fund the club getting materials such as a telescope. Students can also manipulate astronomic data using the skills acquired from TopCat, which is the software we will be using for our research.
- Speaking to the alumni of the Richard Gilder Graduate School Masters of Arts in Teaching Program at the American Museum of Natural History about NITARP, experiences and sharing the research and findings of the research project. Doing so can potentially recruit more NITARP participants and inspire in-service teachers to incorporate astronomy research with their students.