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QUAIA × VLASS: A NEW SAMPLE OF COMPACT EXTRAGALACTIC RADIO SOURCES

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Abstract. Compact radio sources, radio-emitting active galactic nuclei, are scarce objects, yet important as reference points for astrometric, astrophysical, and spacecraft navigation applications. We present over 3900 potential new compact radio sources derived from a cross-match between the Very Large Array Sky Survey (VLASS) radio catalogue and the recently published Quaia quasar catalogue. The VLASS catalogue provides a list of individual radio sources identified at 3 GHz with flux densities $\gtrsim 1$ mJy, while the Quaia catalogue is derived from the *Gaia* optical astrometric catalogue by selecting sources with negligible proper motion and performing a k-means search method on colour–colour parameter spaces to extract quasars. We find more than 45 000 matched sources between the two catalogues with separations less than $2''$ from which more than 3900 present themselves as high-fidelity compact radio source candidates by having radio flux density > 20 mJy and a compactness ratio > 0.8. A proposal for observing 80 of these sources has been accepted by the European Very Long Baseline Interferometry Network which should validate the candidates and provide constraints on the parent sample. A follow-up analysis of the cosmologically important properties of the sources will be valuable, e.g. an analysis of the radio-loudness, its correlation to the spatial density in clusters and voids, and the correlation to colour–colour parameter spaces.

1. INTRODUCTION

Currently, the largest list of compact radio sources observed with very long baseline interferometry (VLBI), the 2024a edition of the Radio Fundamental Catalog (RFC, Petrov & Kovalev 2024), contains almost 22 000 objects targeted in absolute astrometric/geodetic programs since 1980. These include the $\sim$ 4500 extragalactic radio sources in the 3rd realization of the International Celestial Reference Frame (ICRF3, Charlot et al. 2020) at $\sim$ 8 GHz (X band). Apart from obvious astrophysical reasons of studying jet physics in more individual bright radio-loud active galactic nuclei (AGN), there is huge scientific potential in substantially increasing the number of VLBI-detected sources. The many fields that could benefit from such an increase include cosmology (finding much more objects for meaningful tests of cosmological models, e.g. Mosoni et al. 2006, and correlating radio-loudness of quasars with the large-scale structure that these objects are part of, e.g. Li et al. 2022), astrometry (improving the tie between the most accurate optical and radio reference frames, e.g. Bourda et al. 2010), astrophysics (availability of more nearby calibrators for high-resolution VLBI observations of various types of faint radio sources by means of traditional and in-beam phase-referencing, Beasley & Conway 1995), and navigation of interplanetary spacecraft using relative astrometric observations with respect to background AGN (e.g. Gurvits et al. 2023).

The small imaging fields of view inherent in the technique make all-sky VLBI surveys unfeasible. While deep wide-field observing projects (e.g. Njeri et al. 2023) are capable of investigating selected areas and characterising the faint (sub-mJy) AGN population, the sky is generally sparsely populated with compact radio sources having flux densities of tens of mJy or higher. However, these brighter sources would be essential phase-reference calibrators, because the smallest possible target–calibrator separation plays a crucial role in imaging and achieving the most accurate relative position measurements (Rioja & Dodson 2020). Therefore, an efficient method that could be applied to pre-select radio sources suitable for VLBI detection based on existing sky survey data found in the radio and other wavebands, but without wasting much of the precious VLBI observing resources, would be an important contribution to the VLBI community.

2. SAMPLE SELECTION

Most recently, a new all-sky quasar catalogue called Quaia (Storey-Fisher et al. 2024) was constructed based on *Gaia* DR3 (Gaia Collaboration 2023) quasar candidates, and using *Wide-field Infrared Survey Explorer* (*WISE*, Lang 2014) mid-infrared photometry to remove contaminants and improve the precision of photometric redshift estimates. While the primary purpose of Quaia containing $\sim$ 1.3 million objects with $G < 20.5^{\mathrm{m}}$ is facilitating cosmological studies, its high purity and completeness make this catalogue a potentially valuable asset for other applications as well. On the radio side, the ongoing 3-GHz Very Large Array Sky Survey (VLASS, Lacy et al. 2020) offers an excellent opportunity for cross-matching Quaia optical quasars with known radio sources that are compact on arcsec scale.

Among the $\sim$ 1.1 million Quaia quasars at declinations $\delta > -40°$, i.e. the sky coverage of VLASS, $\sim$ 47 000 have unique counterparts within $2''$ search radius (Fig. 1) in the VLASS Epoch 2 catalogue. The estimated false-match probability is $< 0.2\%$

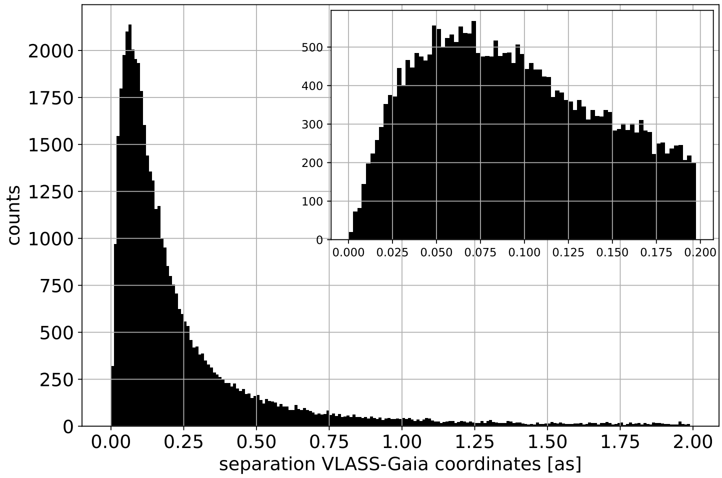

Figure 1: Histogram of the number of cross-matched sources as a function of the separation in VLASS–*Gaia* coordinates. We consider proper cross-matches objects with separations up to 2″, yielding a high completeness. The inlet in the top right is a zoom-in on the range of radio–optical separations from 0 to 0.2″.

(Fig. 2). In particular, 3956 of those satisfy the following radio selection criteria: *(i)* total flux density $S_{3\,\mathrm{GHz}} > 20$ mJy, *(ii)* compactness $C > 0.8$ beam^{-1} defined as the ratio of peak brightness and total flux density, and *(iii)* not contained in the most recent RFC (Petrov & Kovalev 2024) as an already known VLBI source. These 3956 objects are potential new VLBI targets, from which we got approved 80 sources for test observations by the European VLBI Network (EVN).

Optical classification plays an important role in enhancing the chance of VLBI detection of radio sources known at arcsec scale (Deller & Middelberg 2014). Indeed, earlier pilot studies on small samples, based on cross-matching Sloan Digital Sky Survey optical quasars with radio sources from the Faint Images of the Radio Sky at Twenty-Centimeters (FIRST, Becker, White & Helfand 1995) survey at 1.4 GHz (Garrington et al. 1999; Frey et al. 2008) indicated that the VLBI detection rate with phase-referenced observations can be as high as $\sim 90\%$ using simple selection criteria similar to ours. The quality of the Quaia catalogue, as well as the higher frequency and angular resolution of VLASS compared to FIRST, promise an even more favourable selection. However, we are now interested in quasars that are bright and compact enough to enable VLBI fringe-fitting (Schwab & Cotton 1983). A notable benefit of using Quaia is that the accuracy of the *Gaia* quasar coordinates, that can be used as a-priori positions, is comparable to that of VLBI (Kovalev, Petrov & Plavin 2017).

The sizeable sample of 80 objects from the cross-matched Quaia–VLASS list of quasars, that are not yet known as VLBI-detected sources and satisfy the above criteria for flux density *(i)* and compactness *(ii)*, will be subject to observations by the EVN at X band. The primary goals of the project are

- to check, for the first time at X band, how efficient these selection criteria are for pre-selecting potential future VLBI reference sources, without applying phase

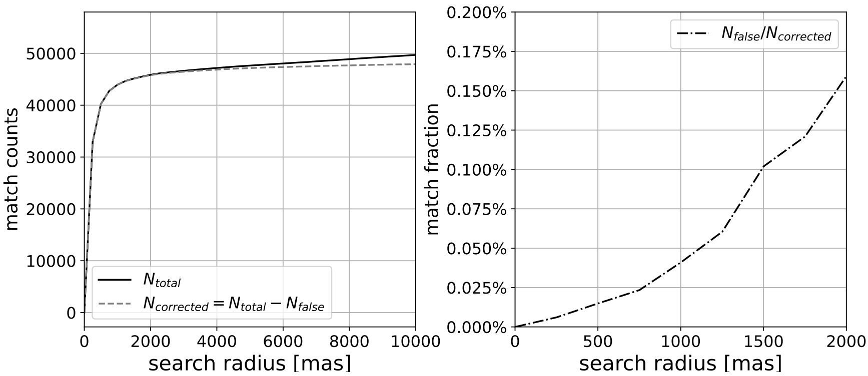

Figure 2: *Left:* The cumulative histogram to Fig. 1 is shown by the N_{total} curve. To estimate the false-match probability, we performed a random rotation of the Quaia catalogue and then cross-matched it with the VLASS one. This gives us N_{false} matches, a proxy for the non-physical cross-matches between VLASS and Quaia that just happen to overlap in the 2D right ascension–declination projection. By subtracting N_{false} from N_{total}, we get a corrected distribution of the true cross-matched sources (dashed curve). *Right:* The contamination $N_{\mathrm{false}}/N_{\mathrm{corrected}}$ of the cross-matches as a function of the search radius. It shows that at the chosen threshold for the cross-matches of $2''$ we expect to have $< 0.2\%$ false matches, meaning a very high purity. The horizontal axes are scaled in milliarcseconds (mas).

referencing;

- to investigate, for further refinements, how the likelihood of VLBI detection depends on various factors like optical magnitude, total radio flux density, arcsec-scale compactness, etc.;

- to estimate how existing all-sky optical and radio catalogues could be utilised for a significant densification of the grid of compact VLBI reference sources for astrophysical and astrometric applications;

- as a by-product, to find additional potential phase-reference sources in a selected region around the Ecliptic, in support of spacecraft navigation;

- as another by-product, to find potential VLBI phase-reference sources in an *Euclid* deep field around the well-studied Northern Ecliptic Pole (NEP) region (Euclid Collaboration 2022).

Assuming that the full sample of nearly 4000 Quaia–VLASS quasars with no existing information about their X-band VLBI structure contains 50% of detectable objects, the probability of determining their true ratio with an error within $\pm 10\%$ by observing a sub-sample of just 80 sources is 63%. In turn, if the true detectability ratio is as large as 80%, our sample proposed here for observations will provide a result with $\sim 91\%$ probability at that level of uncertainty.

For the upcoming EVN observations, we selected two different regions with $40-40$ test sources in each (Fig. 3), to represent the whole Quaia–VLASS sample above $\delta > -40°$. One of them is in the NEP region where the number of Quaia objects is not limited by extinction in the Galactic plane. A secondary benefit of choosing this particular test area is its overlap with one of the deep fields of the *Euclid* space telescope (Euclid Collaboration 2022) of the European Space Agency (ESA). Identifying suitable new VLBI phase-reference sources would help any future radio interferometric observing project here. The other selected region is located close to the northernmost section of the Ecliptic belt. This area of the sky is somewhat closer to the Galactic plane. While around the Ecliptic, it has reasonably good common visibility from the EVN antennas. Here the secondary benefit is the densification of the phase-reference source grid to aid spacecraft navigation. For example, ESA's *JUICE* (Gurvits et al. 2023), en route to Jupiter, will pass this region in mid-Aug 2025, just weeks before its Venus flyby. In terms of VLASS flux density distribution (Fig. 4) as well as radio compactness (Fig. 5), these 80 sources are representative of the whole Quaia–VLASS sample, allowing us to draw more general statistical conclusions after analysing the observations.

The X-band EVN observations (project code: EF033, PI: S. Frey) will take place in the near future (early 2025) in two segments, using a global network of more than 10 radio telescopes in Europe, China, and South Africa. The data will be recorded at the telescope sites and shipped to the central correlator facility at the Joint Institute for VLBI European Research Infrastructure Consortium where the interference is achieved (Keimpema et al. 2015). Upon successful performance, the correlated data are expected to become available for analysis later in 2025.

We intend to make the calibrated visibility data and images of all the detected sources publicly available for the community. After completing the EVN observations and the analysis of the VLBI data, we will be able to statistically express our confidence in the larger catalogue of about 45 000 Quaia–VLASS matches and we will publish the full quasar list.

3. SUMMARY AND OUTLOOK

We selected a total of nearly 4000 radio-emitting AGN by cross-matching the recent Quaia optical and VLASS Epoch 2 radio catalogues with a search radius of $2''$. The selected quasars at declinations north of $\delta = -40°$ have accurate optical astrometric positions from *Gaia* DR3, as well as photometric redshift information. They have flux densities $S_{3\,\mathrm{GHz}} > 20$ mJy and compactness parameter $C > 0.8$ beam^{-1} based on VLASS data. These objects are promising targets for VLBI observations that provide radio images with mas-scale angular resolution. A representative sub-sample of 80 quasars is being observed with the EVN at X-band (around 8 GHz frequency). The results of this pilot project will allow us to estimate the fraction of VLBI-detectable objects in the entire cross-matched Quaia–VLASS sample, leading to an estimate of potential new VLBI target sources, and providing a comprehensive list of them. This would facilitate follow-up observations in various celestial areas of interest. The availability of a large number of yet unknown new VLBI sources would be beneficial for a multitude of potential scientific applications in the fields of astrometry, astrophysics, cosmology, and interplanetary spacecraft navigation.

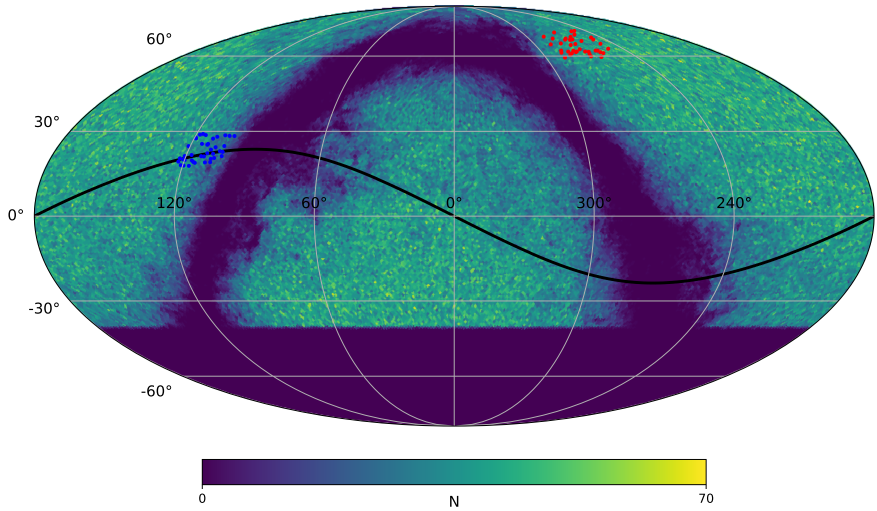

Figure 3: Sky map of the Quaia catalogue (Storey-Fisher et al. 2024) sources north of −40° declination. The shades represent the density of objects, the darkest being the Galactic plane. The matching Quaia–VLASS sources in the two areas selected for test observations are indicated with 40 blue and 40 red dots in the Ecliptic and NEP regions, respectively. The black curve represents the Ecliptic plane.

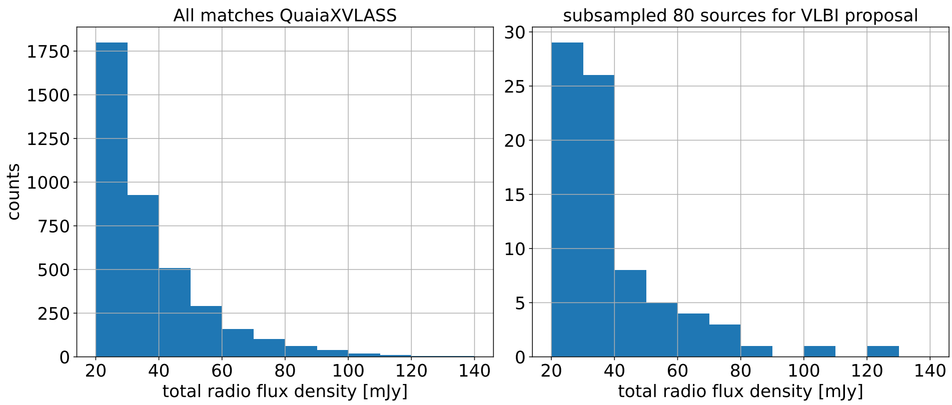

Figure 4: Total VLASS (Lacy et al. 2020) flux density ($S_{3\,\mathrm{GHz}} > 20$ mJy) distribution for the entire matching Quaia–VLASS sample *(left)* and for the representative subsample of 80 sources proposed for EVN observations *(right)*.

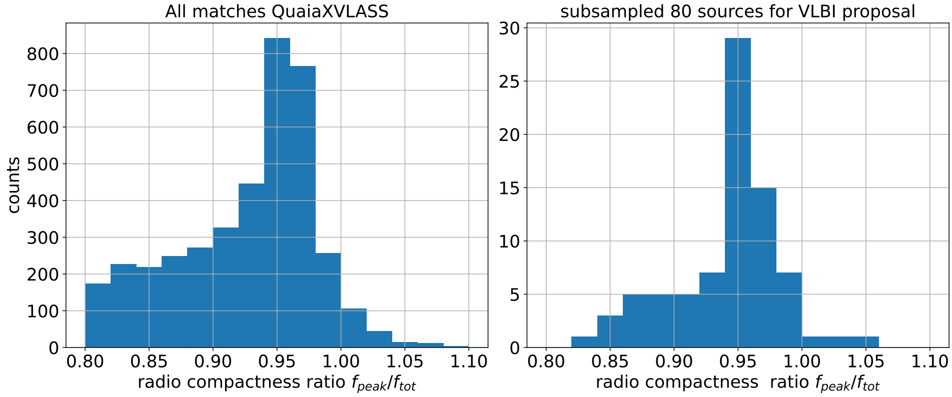

Figure 5: Distribution of arcsec-scale compactness of radio emission based on the ratio of the VLASS peak brightness to the flux density ($C > 0.8$ beam^{-1}), for the entire Quaia–VLASS sample *(left)* and for the representative sub-sample of 80 sources proposed for EVN observations *(right)*.

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