Revealing milliarcsecond optical structure through VLBI observations of Gaia detected AGNs

OPAL LBA Cover Sheet v.1.1

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Proposal Details

Previous proposal number	V561
Previous publications	0
Proposal type	Standard
Pre-graded	No
Scientific categories	active galactic nuclei / quasars
Help required	None
Used for PhD thesis	No

Instrument Information

Antennas requested

- Parkes
- Mopra
- Tidbinbilla (Either Tidbinbilla antenna)
- Hobart
- Ceduna
- Warkworth (12m)
- AuScopeYarragadee
- AuScopeKatherine
- HartRAO
- APT/Other (WARK30M)

Observing mode	Disk recording
Simultaneous ATCA observations	No
Recorder	Mark 5 where possible
Other information	Imaging Point source Astrometry

Correlation location CSIRO (Pawsey)

Abstracts

Science abstract

We request four 24 hour sessions using the LBA for observing a list of 227 Gaia detected active galaxy nuclei at declinations below -50deg that are known VLBI objects. The goal of the proposed observations is to improve position accuracy from 2.6 mas to 0.2-0.5 mas, produce images at X and S bands, and determine jet directions. Analysis of these results together with existing and anticipated Gaia results will enable us to study AGN optical structure at milliarcsecond level that currently cannot be detected directly with optical instruments.

Outreach statement

Telescope resolution is reciprocal to the telescope diameter. The Hubble telescope has resolution about 0.1 arcsec. Combining the array of southern hemisphere radio telescopes and space telescope Gaia, it is possible to study optical structure of active galactic nuclei at resolution 100 times better. In order to detect directly such structure, a space optical telescope with the size of a football field would be necessary.

Scheduling

Special requirements	S/X receiver at Parkes is required. Required antennas: Pa, Ke, Yg, Ho, Ww. Optional: Td, Mp, At, Cd, Wa (X-band only)
Additional information	1 Gbps at Pa, Ke, Yg, Ho, Ww is required for the goal of the project. Other stations can record a part of the bandwidth
Total time for project	**144 hours (previous + this proposal + future requests)**
Allocated time so far	**48 hours (all previous semesters)**

OPAL LBA Observations Table v.1.1

Name	Position			Integration time (hours)	Repeats	Total time	Target type	Band	Polarisations	IFs	Frequencies (MHz)	Bandwidths (MHz)	Transitions	Data rate (Mbps)
	RA	Dec	Epoch											
227 target sources	00:00:00	-89:59:59	J2000	24.0	4	96.0	many sources	S/X	1	16	8400	16		1024

Total time for semester: 96.0 hours

Revealing milliarcsecond optical structure through VLBI observations of *Gaia* detected AGNs

1 Summary

We request four 24 hour sessions at the LBA for observing a list of 227 *Gaia* detected active galaxy nuclei at declinations below -45° that were detected in previous LCS observations (Petrov et al. 2011). The goal of proposed observations is to improve position accuracy from 2.6 mas to 0.2–0.5 mas, produce images at X and S bands, and determine jet directions. Analysis of these results together with existing and anticipated *Gaia* results will enable us to study AGN optical structure at milliarcsecond level that currently cannot be detected directly with optical instruments.

2 Problem statement

Analysis of *Gaia* DR1 released in September 2016 showed (Petrov & Kovalev 2017a, Kovalev et al. 2017) that 1) one half of sources detected in absolute astrometry VLBI surveys have Gaia counterparts; 2) within VLBI/*Gaia* matches, 7% have statistically significant offsets; 3) the distribution of position offset directions has a strong anisotropy with respect to the jet direction (See Figure 1). This suggests that VLBI/*Gaia* position differences that are typically at a 1–3 mas level are not the noise solely due to measurement uncertainties, but a source of valuable information about optical structure. The response to an extended source of an interferometer and a quadratic detector, like CCD, is fundamentally different. Analysis of interferometer data provides us the position of the most compact detail associated with an AGN jet base. A quadratic detector provides us position of the image centroid. We presented extensive argumentation in (Petrov & Kovalev 2017b) that it is the presence of optical structure at milliarcsecond level that causes the shift. Other factors that might cause a *systematic* shift along the jet direction are one order of magnitude too small. Study of the AGN optical structure at scales 1–10 mas is the main objective of this project.

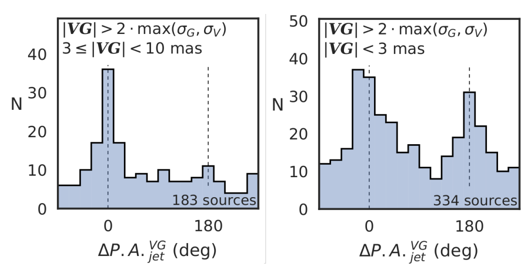

Figure 1: The distribution of $\Delta \mathrm{P.A.}_{\mathrm{jet}}^{\mathrm{VG}}$ for different sub-samples of VLBI-*Gaia* associations with probability of false association less than $2 \cdot 10^{-4}$. The vertical dashed lines are shown for $\Delta \mathrm{P.A.}_{\mathrm{jet}}^{\mathrm{VG}} = 0°$ (VLBI to *Gaia* $\vec{VG}$ reference point offset vector along the jet) and 180° ($\vec{VG}$ offset vector opposite to the jet direction) values. Source: Kovalev et al. (2017). See this paper for a detailed explanation.

3 Goals of the program

Recognizing that VLBI/*Gaia* position offsets offer a unique opportunity to trace the presence of **AGNs optical stricture** at milliarcsecond level, the all-sky program for re-observations of known VLBI sources with matched *Gaia* objects is launched. The goals of the observing program is to improve VLBI position accuracies to 0.3 mas level and determine the directions of jets with accuracies 10–20°. VLBI/*Gaia* position offset time series and light curves accumulated during *Gaia* mission lifetime, radio images, and jet directions will provide us the dataset that will be used for analyzing the sizable population of AGNs (at least 8,000 objects).

In particular, this study will help us to answer the question, in what AGN regions brightening in the optical range occurs during a flare: in the accretion disk (point A in Figure 2), in the jet base (point B), or in the hot spot on the jet (point J). Correlating *Gaia* light curve with time series of $\mathcal{O}_j$ observable that is the projection of *Gaia* position offset wrt VLBI on the jet direction, we can determine the region where the flare has happened: in the accretion disk, in the jet base in in the hot spot. Determination of the jet direction and the VLBI precise position that will anchor the *Gaia* position time series to the jet base is critical for this analysis.

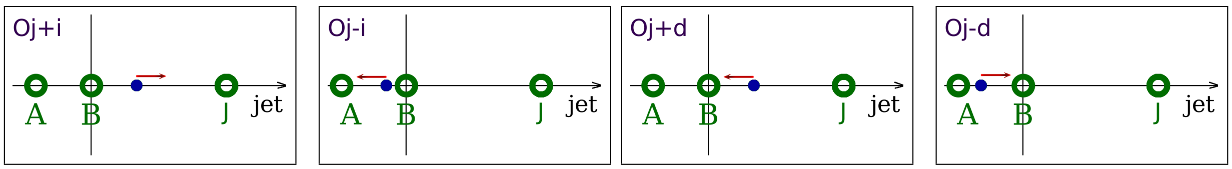

Figure 2: A simplified diagram of the O_j projection changes after a flare in optic range: 1) O_j+i: positive projection increases by modulo; 2) O_j−i: negative projection increases by modulo; 3) O_j+d: positive projection decreases by modulo; 4) O_j−d: negative projection decreases by modulo; The filled **blue circle** denotes the optic centroid. In depth discussion can be found in Petrov & Kovalev (2017b).

Accumulated statistics will also allow us to study the prevalence of AGN optical jets in the population and its relationship with other AGN properties. Statistics of optical brightening and associated shifts of Gaia positions either along or opposite to the jet direction with respect to the VLBI position will allow us to study the prevalence of regions where brightening occurs.

The positions of AGNs in *Gaia* DR1 have a median accuracy of 2.3 mas because the data were analyzed in a coarse mode. This accuracy is close to the accuracy floor of the single-band LBA Calibrator Survey (LCS) (Petrov et al. 2011) caused by mismodeling the ionosphere contribution. Achieved metrics of *Gaia* performance indicate that unless a catastrophic event happen, AGN position accuracy will be improved by an order of magnitude by the end of the mission, and position time series with accuracies better 1 mas will be acquired. There is a challenge to match *Gaia* anticipated accuracy in radio wavelengths in the southern hemisphere.

4 Proposed observations

We have identified a list of 227 sources at declination range $[-90°, -45°]$ with flux densities in a range [70, 300] mJy that have a *Gaia* DR1 or DR2 counterpart[1]. These sources were detected with the LCS, but their position accuracy is limited to 1.6–5 mas (median: 2.6 mas) due to the systematic errors caused by the ionosphere. We request for 4 twenty-four hour observing sessions at dual-band S/X at 1 Gbps to re-observe them. Each target source will be observed in 4 scans for 3 minutes. We require Pa, Ke, Yg, Hb, Ww, Ho, and Hh. We would like Cd, Mp, At, Wa to join at X-band only to improve the *uv* coverage. Although X-band only data will not be used for precise astrometry, they will be used for imaging. Including any Tidbinbilla antenna for a part of the observing sessions is desirable to improving position accuracy. We know that the majority of AGNs show optic variability, but we do not know which source will have a strong flare and a detectable associated position wander during the life time of the *Gaia* mission. In order to have meaningful statistics of the prevalence of flares in the accretion disk, jet base and hot spot, we need to determine the flare origin for 30–50 objects, which requires a large pool of candidates. Thus, our sample has all the sources brighter 70 mJy, but dimmer 250 mJy at $\delta < -45°$, i.e detectable with Pa+Auscope and not reachable by northern hemisphere arrays.

[1] The *Gaia* science team has provided us the list of *Gaia* detected VLBI sources that are not in DR1 and will be likely included in the DR2. The DR2 is expected to have 30% more sources

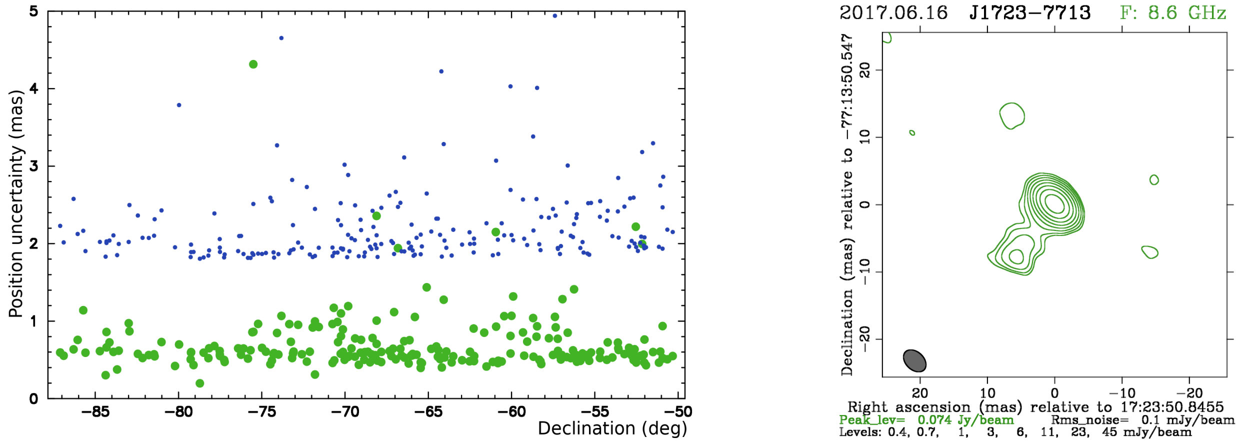

Figure 3: *Left:* Position uncertainty from **prior LCS observations** and **new v561a** observations with accounting for systematic errors; *Right:* an an example of a preliminary image of a source observed in v561a that has never been imaged before. The jet direction is reliably determined.

5 Previous observations

On 16–18 June a list of 226 target sources and 45 calibrators were observed. Of them, 1 was not detected in neither bands, and 6 others had less than 3 detections at S-band. The median position accuracy was improved from 2.1 to 0.6 mas level (see Figure 3), i.e. by a factor of 3.5, and more observations will allow us to reach the goal 0.3 mas accuracy. An example of an image from that experiment is shown in Figure 3 as well.

6 Expected outcome of observations

We will derive source positions with accuracies better 0.3 mas, generate images at X and S band, and determine jet directions. Positions will be derived within 20 days of availability of the correlator output and images within 3 months. Preliminary positions and images will be posted at the project web site and will be incorporated in the Radio Fundamental Catalogue (Petrov & Kovalev in preparation)[2].

7 Connection with another programs

We are going to observe sources in a range of declinations [-45°, -35°] in a separate project involving the Tianma 65m, Kunming 40m telescopes, and the AuScope VLBI array. Sources with declination range [-35°, +90°] which positions or maps need improvement will be observed with the VLBA and EVN. Matching VLBA proposal has been approved for observations in 2018A deadline. The sources brighter than 250 mJy at declinations $< -40°$ are observed within the on-going SOAP program[3] with the Auscope array and Ho-Hh-Ww-Wa. In order to observe weaker target sources with less sensitive but dual-band capable radio telescopes, the Parkes antenna is required.

References

Kovalev, Y.Y. Petrov, L., Plavin, A., (2017), A&A, 598, L1.
Petrov L., Phillips C., Bertarini A., Murphy T., Sadler E. M., (2011), MNRAS, 414(3), 2528–2539.
Petrov, L., Kovalev, Y.Y., (2017a), MNRAS Let, 467, L71–L75.
Petrov, L., Kovalev, Y.Y., (2017b) MNRAS, 471, 3775–3787.

[2]Preview that already includes results of v561 is available at http://astrogeo.org/rfc
[3]See http://astrogeo.org/soap