EUROPEAN VLBI NETWORK

EVN Proposal

RadioNet

JIVE Joint Institute for VLBI ERIC

No code

Petrov

Probing mas-level optical structure with VLBI observations of Gaia detected AGNs

Abstract

The goal of this project is to probe the optical structure of active galactic nuclei (AGNs) at milliarcsecond scales via synergism of VLBI and optical space astronomy techniques. The proposed EVN observations will improve accuracy of determination of projections of Gaia/VLBI position offsets to the jet direction that will be estimated from parsec-scale images for 171 sources. The analysis of Gaia/VLBI position offsets provides reach information about AGNs jets in optical range not accessible from direct observations. We will perform a statistical analysis of Gaia/VLBI offsets using the flux-limited sample. The aim of the statistical study is to decompose factors that cause observed Gaia/VLBI positional offsets: accretion disk, parsec-scale radio/optical cores and jets, host galaxy. Such a decomposition is problematic for individual AGNs, but achievable through analysis of the large complete sample.

Applicants

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Summary of Observations

Observation number	Number of targets	Network	Hours requested	Waveband	Number of epochs	Aggregate bitrate	Correlator	e-EVN	Out-of-session
1	0	EVN, EVN with individual limitations	48.0, 48.0	3.6/13 cm	1	1024	JIVE	No	No

Students involved

Student	Level	Applicant	Supervisor	Applicant	Expected completion date	Data required
Alexander Plavin	Doctor	Yes	Yury Kovalev	Yes	2020/01	Yes

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: No

Additional remarks

This proposal is complmentary to the LBA and VLBA projects that are accepted for 2018A semester. Though the scientifc goals are to some degree overlapping, the source lists are totally different.

1 Introduction

Analysis of the *Gaia* DR1 catalogue of 1.14 billion objects released in 2016 revealed (Petrov & Kovalev 2017a, Kovalev et al. 2017) that the distribution of position offset directions has a strong anisotropy wrt the parsec-scale radio jet directions (See Fig. 1). Offsets less than 3 mas have preferred directions both along and opposite jets. Offsets greater than 3 mas occur predominately along the jet.

Since the distributions of *Gaia*/VLBI offsets and VLBI jet directions with respect to the celestial pole exhibit a great degree of isotropy, we conclude that the alignment of *Gaia*/VLBI offsets along the jet direction is not the noise solely due to measurement uncertainties but has a physical origin.

In Petrov & Kovalev (2017b) we presented extensive argumentation based on results of data analysis, simulations, and modeling showing that the only effect that explains observed anisotropy is the presence of optical structure, other effects such as the contribution of radio source structure to position and core-shift being one order of magnitude too small. **Investigation of the optical structure at milliarcsecond scales is the main goal of our project**. We have demonstrated merit of such investigation in Petrov & Kovalev (2017b) and we propose a project in line with this publication.

2 A model of *Gaia*/VLBI offsets

In Petrov & Kovalev (2017b) we considered the consequences of the milliarcsecond optical structure in detail. We have demonstrated that *Gaia* provides position of a centroid, while VLBI provides position of the jet base (core). We showed that vector **bv** caused by radio source structure (See Fig. 2) can be accounted by using radio images, and vector **Bb** caused by the core-shift can be estimated from multifrequency data using technique demonstrated by Sokolovsky et al. (2011). After reduction for **bv** and **Bb**, the observed projection of the *Gaia* optical centroid offset vector with respect to the VLBI position onto the parsec-scale radio jet direction, **G**, hereafter called $\mathcal{O}_\mathrm{j}$ observable, depends on relative fluxes and positions of the accretion disk **A**, the optical core **B**, and the optical jet **J**. **To unravel the contribution of these factors is the major objective of this study**.

An observed offset is a combination of the contributions of the accretion disk, optical jet base (core), optical extended jet, and random measurement errors that are isotropic. The mean VLBI/*Gaia* position differences taken alone do not allow us to decompose the contributions of these factors for a given source; we can only say in some cases which factor is dominating. But such a decomposition becomes possible when we investigate the entire population.

3 The long-term goal: statistical analysis of the *Gaia*/VLBI offsets using the flux-limited sample

We will improve absolute VLBI positions of *Gaia* radio matching sources, apply reduction for radio source structure, determine the coarse core shift using dual-band observations assuming its dependence on frequency $\sim f^{-1}$, determine VLBI jet directions and form primary observables of this project: projections of the *Gaia* position offset with respect to the VLBI position to the jet direction, $\mathcal{O}_\mathrm{j}$, and to the direction transverse to the jet, $\mathcal{O}_\mathrm{t}$. The $\mathcal{O}_\mathrm{j}$ observable is considered as containing signal — an offset of the *Gaia* centroid due to the optical structure, while the $\mathcal{O}_\mathrm{t}$ observable is considered to be due to other factors that are noise for the current study. We consider that the noise equally affects both the $\mathcal{O}_\mathrm{t}$ and $\mathcal{O}_\mathrm{j}$ observables. We will study the following expected dependencies in detail:

- $\mathcal{O}_\mathrm{j}$ versus radio core dominance defined as the ratio of the core radio flux density to the flux density integrated over the VLBI image. We will investigate, whether low radio core dominance, i.e., larger contribution of jet emission, will correlate with large positive $\mathcal{O}_\mathrm{j}$.
- $\mathcal{O}_\mathrm{j}$ versus Doppler factors, δ (see e.g. Hovatta et al. 2009). We will investigate, whether optical jet will be much brighter for larger Doppler factors. For such sources the optical jet emission should win against the contribution of the accretion disk which emission does not depend on δ and therefore, high-δ jets should show larger positive $\mathcal{O}_\mathrm{j}$.
- $\mathcal{O}_\mathrm{j}$ against optical color. The *Gaia* DR2 scheduled for 2018 Q2 will provide mean flux estimates at G and B filters. We will investigate whether sources with inverted optical spectrum will have larger accretion disk contribution and show smaller positive or even negative $\mathcal{O}_\mathrm{j}$ since the accretion disk peaks in the UV-range (the so-called Big Blue Bump, see, e.g., Elvis et al. 1994).

- $\mathcal{O}_\mathrm{j}$ against object type: radio galaxies, BL Lac objects, quasars. The unified scheme of active galactic nuclei (e.g., Urry & Padovani 1995) explains the difference between the optical classes of AGNs by the difference in observing angle of their jets. We will independently check whether a larger observing angle will result in a larger $\mathcal{O}_\mathrm{j}$ after the disk contribution is taken into account.
- $\mathcal{O}_\mathrm{j}$ against distance for AGNs with known redshift as closer targets are expected to show a stronger effect due the higher linear resolution of the observations. A cosmological evolution of the effect would be interesting to look for but is arguably complicated due to a number of possible biases.

4 Proposed EVN observations

As we have shown in Petrov & Kovalev (2017b), the *Gaia* median accuracy of matching sources will be greater than the accuracy of VLBI starting *Gaia* DR2 and without new dedicated observations the uncertainties of VLBI positions will be dominating the error budget. In order to address this problem, we have launched the all-sky observing program with the LBA[1], VLBA[2], and the EVN. **We propose EVN observations with the goal a) to increase the sample size, b) improve accuracy of $\mathcal{O}_\mathrm{j}$ projections by a factor of 3 to the 0.3 mas level, and c) reach completeness**. We will 1) derive source images; 2) improve the VLBI absolute positions with source structure contribution applied, 3) determine their coarse core-shifts, and 4) determine accurately jet directions.

We propose to observe 171 *Gaia*/VLBI matches selected according to the following criteria: 1) declinations above −40°; 2) total flux density at 8.6 GHz integrated from VLBI images > 150 mJy at 8 GHz; 3) either position errors worse 0.3 mas or radio jet direction was not reliably determined because an existing image was of poor quality. The positions and their uncertainties are drawn from the RFC catalogue that is available at `http://astrogeo.org/rfc` (Petrov & Kovalev, 2018, in preparation). The catalogue is 95% complete at the 150 mJy 8 GHz correlated flux density level. Combined with other sources selected in criteria 1 and 2 that already have position errors better 0.3 mas and reliable jet directions, and with planned observations on other array, the resulting sample of 2251 objects will become **a flux limited sample**.

We propose to observe each target source in 6 scans of 60 s each with the S/X receiver in absolute astrometry mode. Every 1.5 hour we will include a block of 4 strong sources selected in such a way that each antenna observes two sources at elevations in a range of [7°, 30°] and sources in a range of [50°, 88°]. Observations of these sources will be used for improving estimates of residual atmospheric path delay, for tying the new catalogue with the past catalogues, and for bandpass calibration.

4.1 Sample size needed for proposed study

In order to avoid selection biases, we struggle to reach completeness of our sample at a given flux density limit. At the moment, only 7.7% sources show a statistically significant offsets mainly because *Gaia* DR1 disfavored extragalactic sources. After *Gaia* DR2, we expect the share of these sources will noticeably increase, but still be well below 50%. Completeness of the RFC naturally suggests the sample size that we can relatively easy observe. We need a dense coverage of objects on different properties being investigated: Doppler factor and observing angle, sources classes and redshift, accretion disk dominance and jet power. A large sample also increases the likelihood of capturing data during flaring events, which can reveal considerable information about the optical structure.

5 Data release plan

The deliverables of the project 1) all calibrated visibilities and images in FITS format, as well as gif-pictures; 2) catalogue of source positions corrected for source structure; 3) jet directions; 4) core shifts; and 5) *Gaia*/VLBI offset vectors will become accessible from the project web site within six months after the release of the correlator output.

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[1] `http://astrogeo.org/soap`

[2] `http://astrogeo.org/vg`

References

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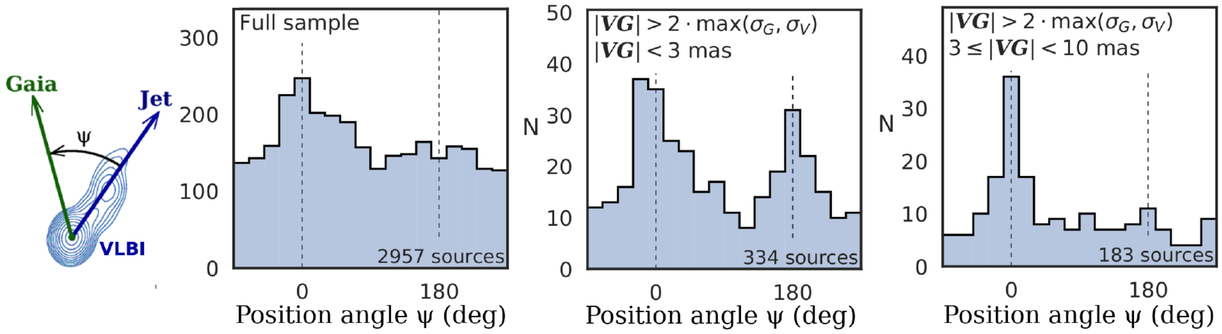

Fig. 1: The distribution of *Gaia*/VLBI offset directions with respect to the radio parsec-scale jet direction. *Left:* full sample of *Gaia*/VLBI matches with the probability of false association less than $2 \cdot 10^{-4}$ and with reliably determined jet directions. *Center and Right:* the distribution for sub-samples of *Gaia*/VLBI matches only with statistically significant offsets. *Center:* a sub-sample of position offsets less than 3 mas. *Right:* a sub-sample of position offsets in a range of 3–10 mas. Source: Kovalev et al. (2017).

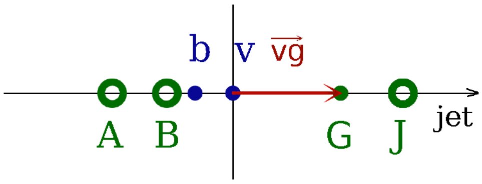

Fig. 2: A simplified diagram of the AGN structure. **v** shows the VLBI position. It is shifted along the parsec-scale radio jet with respect to the apparent VLBI jet base **b** (the radio core) due to unaccounted radio source structure contribution. The optical centroid **G** is a superposition of the emission from the accretion disk **A**, apparent *Gaia* jet base (the optical core) **B**, and optical jet **J**. Astrometric observations provide us the *Gaia*/VLBI offset $\vec{\mathbf{vg}}$ while VLBI imaging allows us to measure the radio jet direction.

Observation details of observation 1

e-EVN observation?

No

Waveband requested

3.6/13 cm

Global Network standard bands

Requested telescopes, times per network

Network	Requested telescopes	Hours	GST Range
EVN	Ef, Mc, Nt, On-60, Tm65, Ur, Ys, Hh, Sv, Zc, Bd	48.0	0-24
EVN with individual limitations	Km	48.0	0-24

Out-of-session observation?

No

No Preferred VLBI session or range of dates for scheduling

No Dates which are NOT acceptable

Recording format specification (detailed setup)

Number of polarizations :	1	***Number of bits per sample:***	2
Number of subbands per polarization :	16	***Number of basebands :***	16
Bandwidth per subband :	16 MHz	***Number of Msamples per second per subband:***	32
Oversampling :	1	***Aggregate bitrate :***	1024 Mbps

Special issues:

We request 1 pol wtih 6 BBC allotted for S-band and 10 BBC allotted to X-band -- a traditional geodesy/absolute astrometry mode. We will be happy if the experiment be recorded at 2Gbps, but considering the amount of recording media is the EVN bottleneck, we agree the experiment be recorded at 1Gbps.

Multi-epoch observation

No Multi-epoch observation

Processor Information

Processor	Special Processing	Averaging time	Spectral channels per Baseband channel	Max. antennas	Independent correlator passes
JIVE	no	1	64	12	1

Target selection criteria:

1) Gaia/VLBI counterpart with the probability of false association less than 0.0002 AND

2) declination > -30 deg AND

3) correlated flux density at 8 GHz > 150 mJy AND

{ 4a) lack of high quality VLBI image that allows to determine jet direction OR

4b) position uncertainty worse than 0.3 mas

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No phase reference sources defined