VLBI and Gaia: a new window to study physics of active galactic nuclei

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Data

VLBI Radio Fundamental Catalogue (13,036 sources) on 2017.04.15 and Gaia DR1 (1.14 · 10^9 objects)

Green: 6,907 VLBI/Gaia matches  \( P < 0.0002 \)

Blue: VLBI sources without Gaia matches
VLBI and Gaia position uncertainties

Median error: **VLBI RFC**: 0.5 mas
Median error: **Gaia DR1**: 2.2 mas
There are \textbf{486 outliers} (7\%) at significance level 99\%.

Outliers range: 1–400 mas (median: 10 mas).
Main finding: no preference at $0^\circ, 180^\circ$ (VLBI declination errors)
No deviation from the isotropy.
How the AGNs look like at mas scale?

Generic property: core-jet morphology:

- Images are available for 74% sources (the number will increase)
- Jets can be reliably determined at 50% images (can be improved)

AGNs are intrinsically asymmetric sources!
Distribution of AGN jet directions in the VLBI/Gaia sample

No deviation from the isotropy
Distribution of VLBI/Gaia position offset angles with respect to jet direction

VLBI/Gaia offsets prefer directions along the jet!!

The pattern can be explained only by core-jet morphology.
VLBI/Gaia differences: explanation

Facts:

- There are 7% sources with significant VLBI/Gaia offsets (1–400 mas).
- While position angles of VLBI/Gaia offsets and jet position angles, taken separately, are distributed uniformly, their difference has significant peaks at 0 and 180 degrees.

To explain the pattern, systematic shifts VLBI/Gaia at 1–2 mas level are required.

Possible explanations:

- **Blame radio:** core-shift;
- **Blame radio:** the contribution of source structure to VLBI positions;
- **Praise Gaia:** the contribution of optical jets or the accretion disks to centroid positions.
Core-shift

- Core is the optically thick part of the jet;
- Core centroid is shifted with respect to the jet base;
- The shift is frequency dependent;
- Results of core-shift measurements:
  - Contribution to 8 GHz positions: $\sim 0.2$ mas;
  - Contribution to dual-band positions: 0.02–0.05 mas.

Conclusion: the effect is too small
Contribution of source structure to VLBI position

- VLBI does not measure position of the centroid
- Source structure contribution depends on image Fourier transform
- The most compact image component has the greatest impact on position
- Examples:

  - Test VLBI experiment processed with source structure contribution applied:
    - Median VLBI position bias: 0.06 mas
    - Median image centroid offset: 0.25 mas

Conclusion: the effect is too small
Contribution of optical structure

There are over 20 known optical jets with sizes $0.5-20''$.

At $z=0.07$, visible optical jet of J1145+1936 would shift centroid at 5 mas.

At $z=0.3$, visible optical jet of J1223+1230 would shift centroid at 1.2 mas.

Conclusion: known optical jets at farther distance can cause centroid shifts at 1–2 mas level.
Optical jets interpretation

Dilemma:

- large optical jet that we see, do not affect Gaia.
- small optical jet that we do not see, affect Gaia.

What are observational consequences?

Image centroid and, therefore VLBI/Gaia offsets will change due to

1. optical variability and
2. jet kinematics.

1959+650 light curve
Jet kinematics

Core ejects components, they are moving, fainting, disappearing

1226+023 at 15.3 GHz, MOJAVE Survey

Epoch (years) Lister et al. (2009)

J1828+4844 centroid evolution

Centroid offset (mas)

Time (years)
Centroid of a core-jet morphology

\[ C_{\text{image}} = \frac{C_{\text{core}} F_{\text{core}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} + \frac{C_{\text{jet}} F_{\text{jet}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} + \frac{C_{\text{stars}} F_{\text{stars}}}{F_{\text{core}} + F_{\text{jet}} + F_{\text{stars}}} \]
Direction of the centroid change after a flare

- **Oj+i**: Flare happened at the jet
- **Oj-i**: Flare happened at the accretion disk
- **Oj+d**: Flare happened at the core or accretion disk
- **Oj-d**: Flare happened at the core and the jet
Correlation of the centroid wander and light curve

1. Two component stationary model

\[ C_f(t) = F(0) \frac{O_j(t) - O_j(0)}{F(t) - F(0)} + O_j(t) \]

\[ F_f(t) = F(0) \frac{O_j(0)}{C_x(t)} \]

We can locate the position of the flaring component and its flux density; stability of \( C_x(t) \) provides a stationarity test.
Correlation of the centroid wander and light curve

2. A general non-stationary model

\[
O_j(t) = \sum_i v(t - t_{0i}) F_j(t) + C_i(t_{0i}) F_j(t_{0i}) \]

\[
F_t(t) = F_c(t) + \sum_i F_j(t) 
\]

\[
F_j(t) = 0 \quad \forall \, t < t_{0i}
\]

Not solvable without a use of addition information

3. Two-component non-stationary case

\[
F_j(t) = \frac{O_j(t) F_t(t) - O_j(t_b) F_t(t_b)}{v(t - t_b)} + F_j(t_b)
\]

\[
F_c(t) = F_t(t) - F_j(t_b)
\]

\[
d_j(t) = d(t_b) + v(t - t_b)
\]

If ejection start time \( t_b \) and component speed \( v \) are known, we can

- locate the **position** of the jet component
- determine its **flux density** as function of time
- determine **flux density** of the core as a function of time
AGN position jitter

A consequence of VLBI/Gaia offset optical jet interpretation is prediction of AGN jitter in Gaia time series at a level of several milliarcseconds.

A jitter is

a) stochastic;
b) confined to a small region;
c) correlated with light curve;
d) occurs primarily along the jet;
e) mean with respect to VLBI position is not zero.

**Naive model:** an AGNs is point-like and stable;

**Realistic model:** AGN has variable structure and it has jitter.

In VLBI world we got used to that.
How to live with AGN position jitter?

Two cases:

- Radio-loud AGNs:
  weak remedy: determine VLBI, jet direction, $O_j(t)$, $O_t(t)$,
  strong remedy: centroid modeling, determination of the invariant core;

- AGNs without detected parsec-scale emission:
  determination of jet direction for position jitter;

Good news: position jitter converges with time to some (biased) mean position.
Future observing programs

- improve VLBI positions of $\sim 6000$ matches at $\delta > -40^\circ$ and get jet directions. Goal: 0.2 mas. Status: pending.

- improve VLBI positions of $\sim 2000$ matches at $\delta < -40^\circ$, get jet directions. Goal: 0.4 mas. Status: approved.


Summary:

- VLBI/Gaia residuals have systematics caused by core-jet morphology;
- VLBI position is related to the most compact detail, an AGN core;
- Gaia position is related to the image centroid within the PSF;
- The most plausible explanation: optical jet at scales 1–200 mas;
- Consequence of the optical jet presence: source position jitter;
- Position jitter + light curve = optical resolution at mas scale;
- Can determine the region of optical flares its kinematics and its flux density.

References:  arxiv.org/abs 1611.02630, 1611.02632, 1870281
http://astrog eo.org/rfc