AGN physics from multi-epoch core-shift measurements

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June 15, 2017
Half a Century of Blazars and Beyond
Core shift in AGN jets

Due to synchrotron self-absorption (e.g. Blandford & Konigl, 1979), the apparent jet origin (core) location $r_c$ depends on $\nu$. The radio core at different frequencies ($\nu_5 > \nu_4 > \nu_3 > \nu_2 > \nu_1$) is illustrated in the diagram.
Observational data

- Simultaneous 2 and 8 GHz VLBA+ observations during 1994-2016 years
- About 1000 of 4000 quasars have noticeable extended jet
- 40 of them observed at > 10 epochs
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- 40 of them observed at > 10 epochs

Blue — all 4143 AGNs
Red — 40 studied here

Redshifts
up to $z = 2.37$,
median $z = 0.74$
Core shift measurement

1. Acquire two-frequency calibrated images
2. Align corresponding images (i.e. find $r_{1 \rightarrow 2}$)
3. Estimate core position on each image — $r_1, r_2$
4. Core shift is $r_c(\nu_1) - r_c(\nu_2) = r_1 - r_2 - r_{1 \rightarrow 2}$
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We developed an automated method.

8 GHz phase center

8 GHz core

2 GHz core

2 GHz phase center

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Core shift magnitudes

40 quasars
1691 individual observations
Magnitude of 8→2 GHz shift:

Median 0.55 mas

Median 3.2 pc
Core shift magnitudes

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Magnitude of 8→2 GHz shift:

Median 0.55 mas
⇒ $r_c(8 \text{ GHz}) = 0.2 \text{ mas}$

Median 3.2 pc
⇒ $r_c(8 \text{ GHz}) = 1 \text{ pc}$

assuming $r_c(\nu) \sim 1/\nu$
Detected 8-2 GHz core-shift variability

Characteristic examples:

Median $\text{max} - \text{min}$ difference 0.35 mas, maximum around 0.8 mas

Significant variability for 33 of 40 AGNs
Find that $r_c \sim S_c^{0.3}$ \implies N_c \sim S_c^{1.5}$ and $B_c \sim S_c^{-0.33}$
Flare propagation

Flare reaches core at $\nu_2$

Flare reaches core at $\nu_1$ while still affecting $\nu_2$

Flare leaves the $\nu_2$ core region

Flare leaves both core regions

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Core position varies by $\sim 0.5$ mas $\Rightarrow$ flare region extent is at least this long
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Flares at $\nu_1$ and $\nu_2$ happen with a delay $\Rightarrow$ cores $r_c(\nu_1)$ and $r_c(\nu_2)$ move separately $\Rightarrow$ any fixed dependency like $r_c \sim 1/\nu$ cannot hold.
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- Apparent core is not only shifted from the jet base, but the shift varies in time;
- Need to take variability of $\Delta r_c$ into account when inferring physical parameters.
Apparent core velocity

Comparison with 15 GHz kinematic measurements:

Core velocity: lower bound on the jet flow speed.
Summary

- We measured 8-2 GHz core shift for the largest sample of AGN observations; typical values are $\sim 0.5$ mas;
- Variability detected for the majority of AGNs: up to $0.8$ mas, typically $\sim 0.3$ mas;
- Cores at different frequencies move separately from each other: no fixed frequency dependence.
- Flare regions are extended along the jet, $\geq 2$ pc.
- Independent method to probe flow speed: apparent core velocity as a lower bound.
Individual core movements

Assuming changes in $S_c$ and $r_c$ caused by jet parameters changing, we get $r_c(\nu) \sim S_c(\nu)^{p}$.

$$\Delta r_c = \begin{align*}
a \\
+ b_1 S_c(\nu_1)^{p} \\
- b_2 S_c(\nu_2)^{p} \\
+ c \cdot r_{\text{beam}}
\end{align*}$$

Measured value

Core movement at $\nu_1$

Core movement at $\nu_2$

Bias due to finite beam

All terms are significant.

No time shift between $S_c(\nu)$ and $r_c(\nu)$ variations.

$p \approx 0.3$