Resolving the Geometry of the Innermost Relativistic Jets in Active Galactic Nuclei

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In the current paradigm, it is believed that the compact VLBI radio core of radio-loud active galactic nuclei (AGNs) represents the innermost upstream regions of relativistic outflows. These regions of AGN jets have generally been modeled by a conical outflow with a roughly constant opening angle and flow speed. Nonetheless, some works suggest that a parabolic geometry would be more appropriate to fit the high energy spectral distribution properties and it has been recently found that, at least in some nearby radio galaxies, the geometry of the innermost regions of the jet is parabolic. We compile here multi-frequency core sizes of archival data to investigate the typically unresolved upstream regions of the jet geometry of a sample of 56 radio-loud AGNs. Data combined from the sources considered here are not consistent with the classic picture of a conical jet starting in the vicinity of the super-massive black hole (SMBH), and may exclude a pure parabolic outflow solution, but rather suggest an intermediate solution with quasi-parabolic streams, which are frequently seen in numerical simulations. Inspection of the large opening angles near the SMBH and the range of the Lorentz factors derived from our results support our analyses. Our result suggests that the conical jet paradigm in AGNs needs to be re-examined by millimeter/sub-millimeter VLBI observations.

An Old Paradigm, Ready to be Updated?

In the current paradigm, it is believed that the compact VLBI radio core of radio-loud AGNi represents the innermost upstream regions of relativistic outflows. These regions of AGN jets have generally been modeled by a conical outflow with a roughly constant opening angle and flow speed.

Nonetheless, some works suggest that a parabolic geometry would be more appropriate (e.g., M87: Asada & Nakamura 2012; NGC 6251: Tseng, et al. 2016; 3C 273: Akiyama et al. 2018; NGC4261: Nakahara et al. 2018; Cyg-A: Nakahara et al. 2018, ApJ submitted).

...Is the old paradigm wrong?

Methodology

Unfortunately, in most of the sources, the transverse section of the jet is not well resolved and it is difficult to check if this trend is a paradigm for all AGNi. In order to study the jet sizes upstream, we take advantage of the core shift:

- The core is a probe for the upstream jet regions
- The core shift provides the location of this region

Probing the core size
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probing the upstream jet size at distance given by core shift.

We compile multi-frequency core sizes of archival data in order to investigate the typically unresolved upstream regions of the jet geometry of a sample of 56 blazars. See Algaba et al (2016) for details.

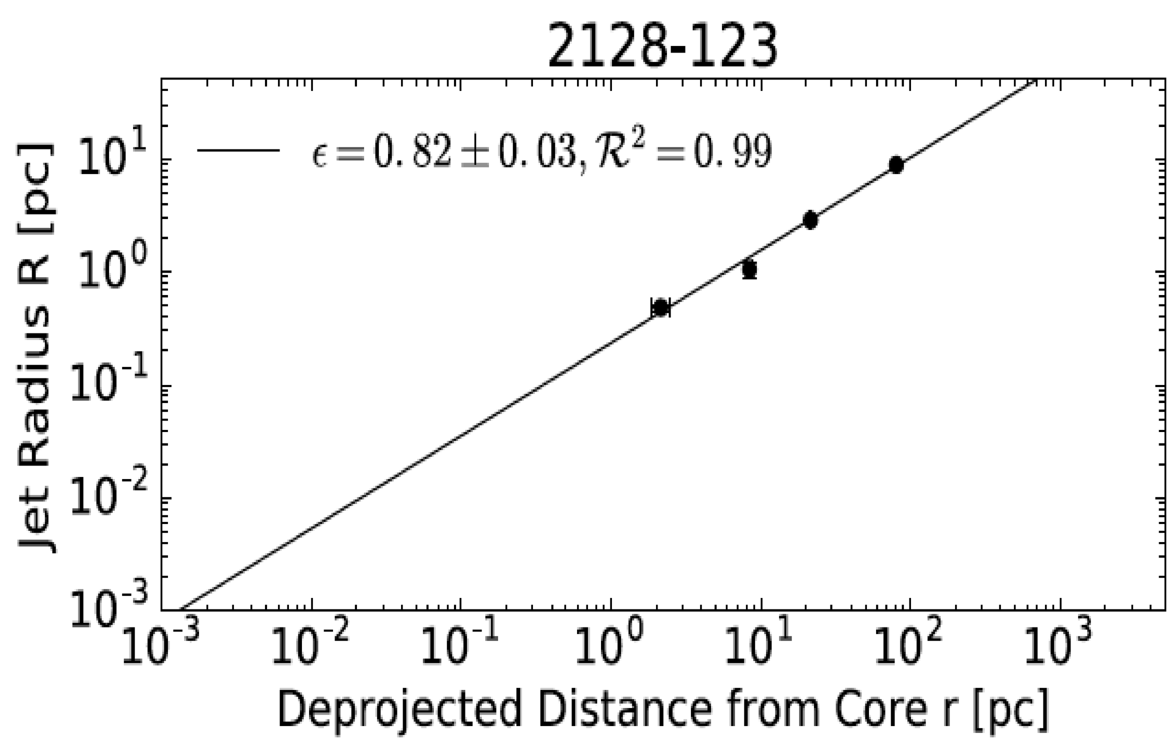
Freq. (GHz) (1)	Instrument (2)	Epoch (3)
1.6	11–16 × VLBI[b]	1990–1991
2.3	VLBA	1998–2003
5.0	VSOP	1997–2002
8.6	VLBA	1998–2003
15	VLBA	1994–2003
22	6 × VLBI[b]	1993
86	GMVA	2001–2002

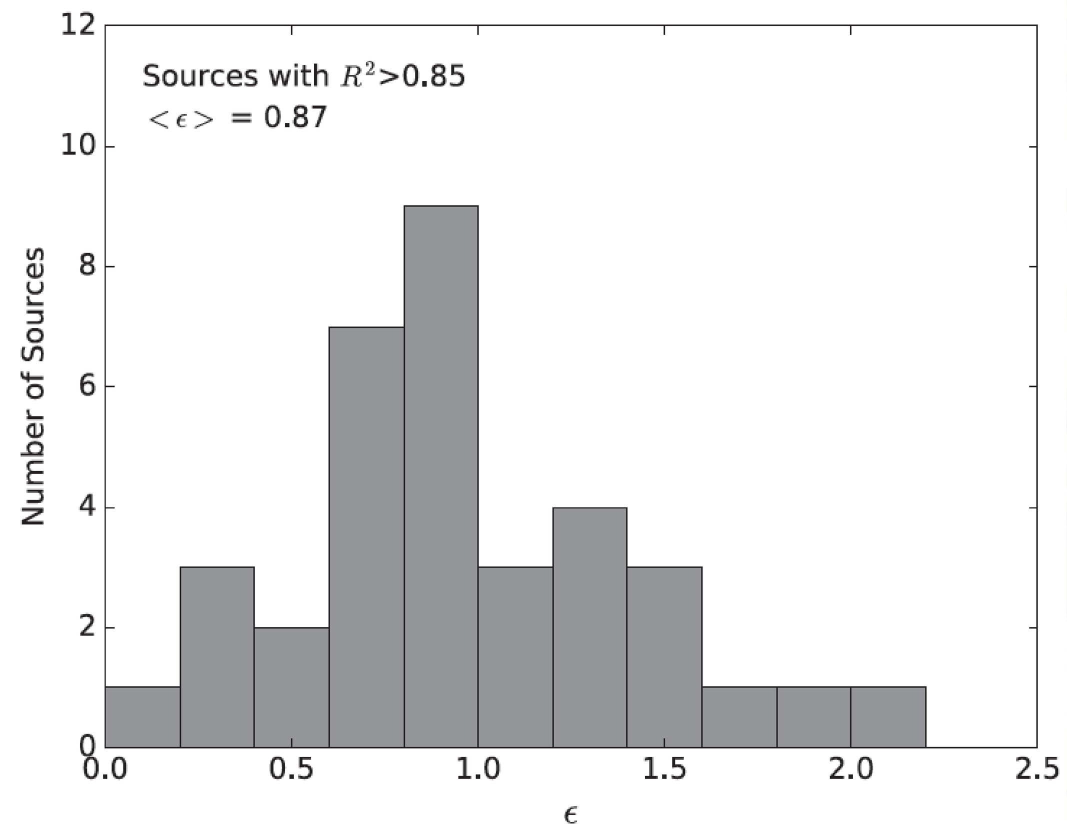
Signs of a New Jet Geometry?

The jet geometry can be parametrized with transverse radius $R \sim r^{\epsilon}$ (r : distance from the nucleus). The jet half opening angle ℝ=arctan(R/r) is thus

- Constant (conical; ballistic jet) if $\epsilon = 1$
- Decreases (parabolic; collimating jet) if $0 < \epsilon < 1$

Although with caveats and limited amount of data, our source-by-source results suggest that there is a significant peak in the number of sources following a semi-parabolic geometry.

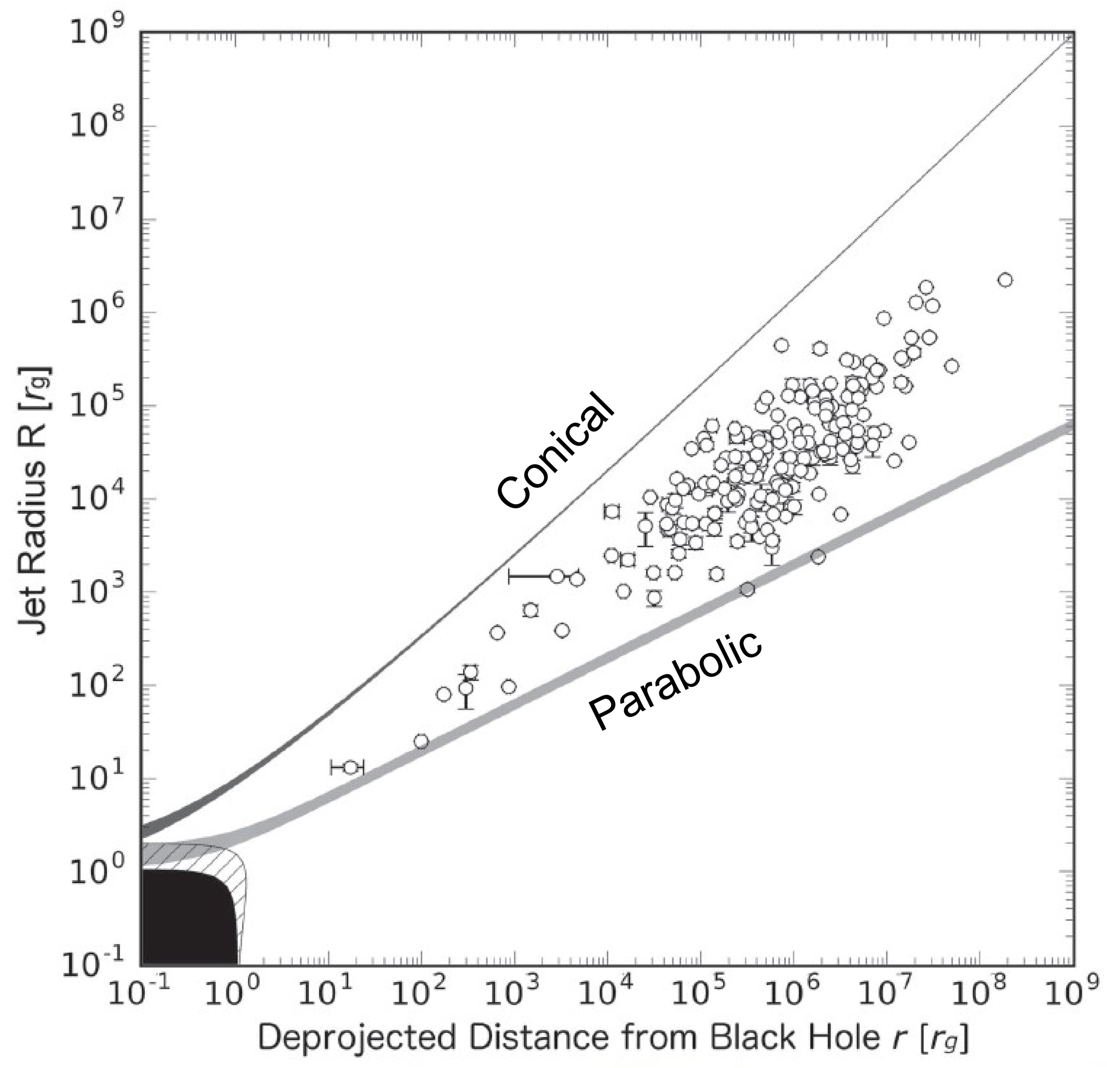


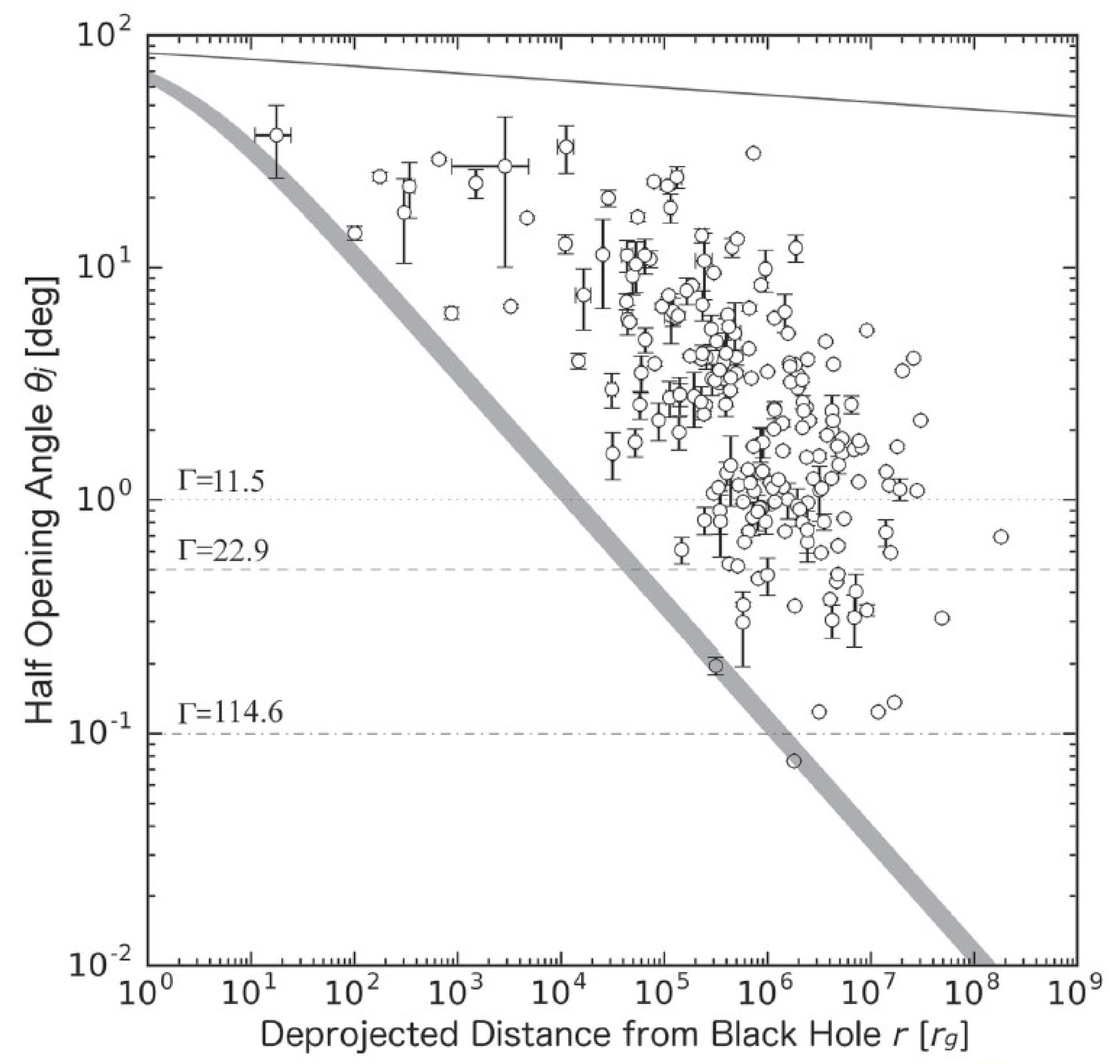


A New Jet Paradigm

Data combined from the sources considered here are not consistent with the classic picture of a conical jet starting in the vicinity of the super-massive black hole (SMBH), and may exclude a pure parabolic outflow solution, but rather suggest an intermediate solution with quasi-parabolic streams, which are frequently seen in numerical simulations.

Half opening angles appear very wide near the black hole, becoming smaller with distance, suggesting collimation is occurring. The jet is then expected to be causally connected with its symmetry axis, implying $\Gamma\theta < 1$ (e.g., Komissarov et al. 2009; Tchekhovskoy et al. 2009). Assuming $\Gamma\theta \sim 0.2$ (Clausen-Brown et al. 2013), derived values of $\Gamma \sim 10$–20 we find are in agreement with values of $\Gamma \sim 15$ from observations by, e.g., Jorstad et al. (2005) and Hovatta et al. (2009), which indicates that the derivation of half opening angles from core size analyses is reasonable.





The light gray area denotes the genuine parabolic streamline, while the dark gray area denotes the quasi-conical streamline. A variation from 0.5<a<0.998 is considered as a shaded area. Left: Filled black region denotes the black hole, while the hatched area represents the ergosphere for the black hole spin parameter a=0.998. Right: Dotted, dashed, and dotted–dashed lines show Lorentz factors for 1°, 0°. 5, and 0°.1, respectively.

Conclusions

- With our criteria, 60% of the sources show quasi-parabolic structure, with $1/2 < \epsilon < 1$, and the median geometry value is $<\epsilon> = 0.85$.
- A semi-parabolic jet shape may be more common near the innermost few parsecs of the jet, in contrast with the conical shapes typically found on deca-parsec scales or further.
- Our result suggests that the conical jet paradigm in AGNs needs to be re-examined by millimeter/sub-millimeter VLBI observations.
- We speculate that the quasi-parabolic streamlines discussed here may not extend beyond the SGI of the SMBH, and a transition from parabolic to conical geometry may occur.

References

- Algaba et al. 2016, ApJ 834, 65
- Asada & Nakamura 2012 ApJ 745, 28
- Akiyama et al. 2018, Galax 6, 15
- Clausen-Brown et al. 2013 A&A 558, 144
- Hovatta et al. 2009 A&A 494, 527
- Jorstad et al. 2005 AJ 130, 1418
- Komissarov et al. 2009 MNRAS 394, 1182
- Nakahara et al. 2018 ApJ 854, 148
- Nakahara et al. 2018 ApJ submitted
- Tchekhovskoy et al. 2009 ApJ 699, 1789
- Tseng, et al. 2016 ApJ 833, 288