AGN Jets are X-ray Variable on kpc scales

Eileen Meyer[1], Aamil Shaik[1], Y. Tang[2], N.I. Reid[3], K. Reddy[1,4], P. Breiding5, M. Georganopoulos[1,6]

[1]University of Maryland Baltimore County [2]Imperial College London [3]U. Of Toronto [4]Arizona State University. [5]Johns Hopkins U. [6]NASA Goddard Space Flight Center

Abstract

Super-massive black holes residing at the centres of galaxies can launch powerful radio-emitting plasma jets which reach scales of hundreds of thousands of light-years, well beyond their host galaxies.[1] The advent of Chandra, the only X-ray observatory capable of sub-arcsecond-scale imaging, has lead to the surprising discovery of strong X-ray emission from jets on kpc scales.[2,3] The origin of this X-ray emission, which appears as a second spectral component from that of the radio emission, has been debated for over two decades.[4] The most commonly assumed mechanism is inverse Compton upscattering of the CMB by very low-energy electrons in a still highly relativistic jet (IC/CMB).[5,6] Under this mechanism no variability in the X-ray emission is expected. Here we report the detection of X-ray variability in the large-scale jet population, using a novel statistical analysis of 53 jets with multiple Chandra observations.

Methods

Our sample comprises all known X-ray jets* imaged more than once by Chandra (ACIS) for a total of 53 sources. After aligning and stacking all available epochs, radio and X-ray imaging was used to identify distinct emitting regions (knots) as shown in **Figure 1.** The typical scale of the variability is shown in **Figure 2.**

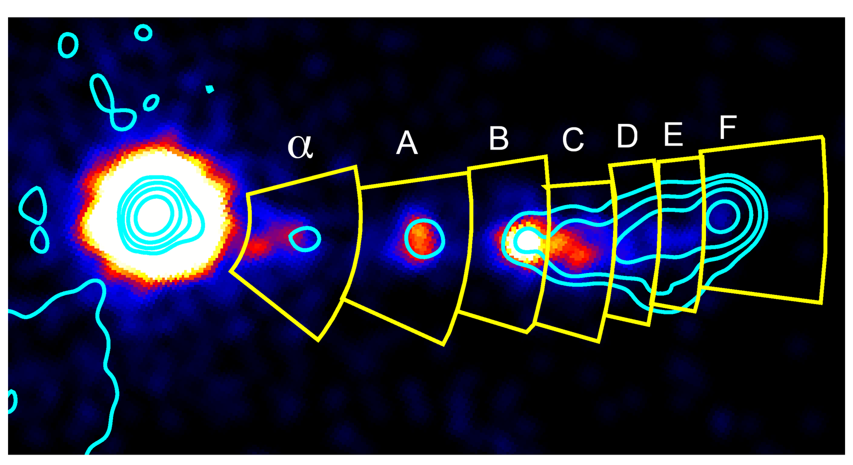


Figure 1 | Smoothed X-ray image of PKS 1136-135, one of the 53 jets in our sample. The regions outlined in yellow and labeled are individual emitting regions (knots) identified through a cross-comparison of the radio and X-ray structure; knot B appears variable in our analysis.

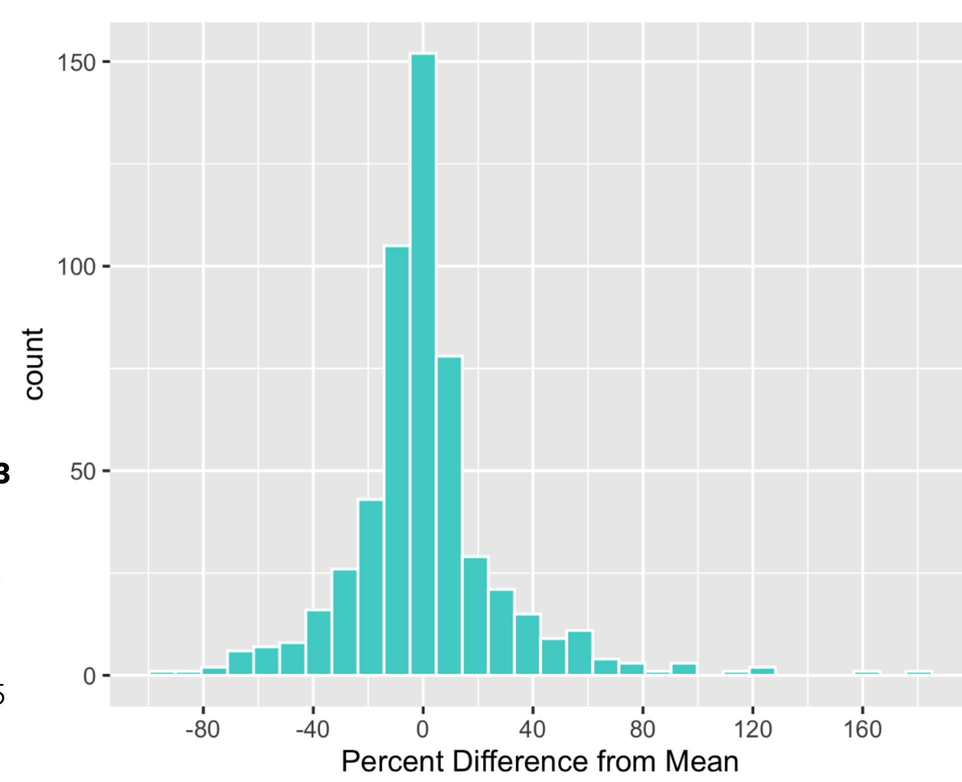


Figure 2 (right) | Histogram of the percent difference of each epoch source rate from the mean for all regions. In all there are 545 distinct observations. The distribution has a mean of 1.02% and a standard deviation of 28.5%. The mean of the absolute value of the percent difference is 18%, which gives a rough scale of the variations.

The likelihood function is a straightforward application of Poisson statistics. We compute for each knot a p-value for the test of the the null hypothesis of a steady source rate, and a maximum-likelihood estimate of the mean count rate for the knot. If the X-ray emission from the tested regions are non-variable, these single-region p-values for the full sample of 155 knot regions are expected to follow a Uniform (0,1) distribution.

Sensitivity

It is useful to examine the effect of the observation characteristics on our results. In particular, we have defined a metric which we call the sensitivity threshold or ST, which is designed to roughly capture the level of variability we can detect for any given region given the actual observations of it in our study. In essence, these numbers define the percent change in flux, negative and positive, that would be necessary for our test to return a single-region p-value < .05. Above all else, this metric demonstrates the limitations of our study. The median values for the ST higher and lower limits are 82.7% and −47.5%. This means that for half of the knots in our sample, we are not sensitive to tens-of-percent variability from the mean, and these regions would only be noted as variable if they underwent relatively large changes of a factor of 2 or more

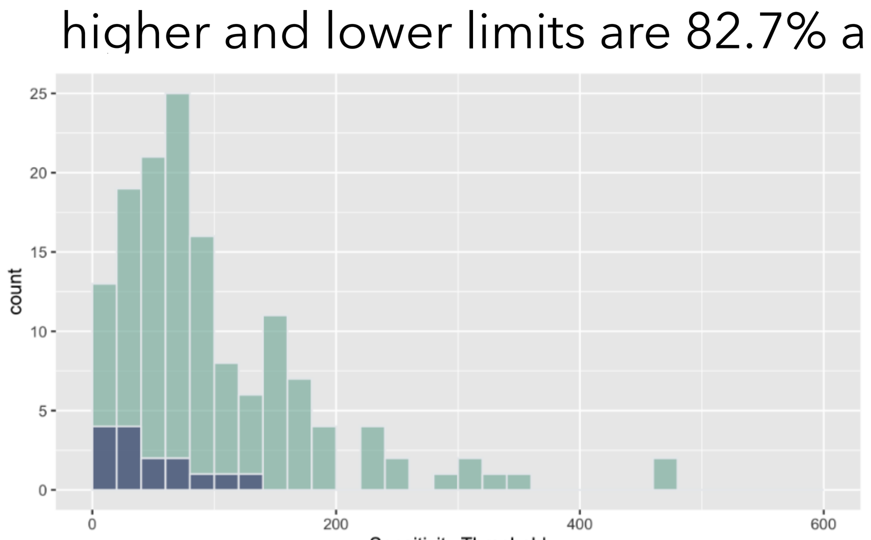


Figure 3 | The green histogram shows the maximum Sensitivity Threshold values as a percentage relative to the mean) for most of our sample. The subset of regions with single-region p-values less than 0.05 are shown in blue.

Results

We compare all 155 single-region p-values to a U(0,1) distribution using a one-sided Kolmogorov-Smirnov (KS) test, and found a significant excess of low p-values. The p-value for testing the uniformity of the single-region p-values by the KS statistic is 1.96e-4 This clearly implies intrinsic variability in the population, beyond simple statistical fluctuation. Assuming that the population of X-ray-emitting jets may be a mixture of truly steady and variable jets, for an observed single-region p-value distribution there is a trade-off between the fraction of the sample which is intrinsically variable and the amplitude of that variability. The resulting p-values from the KS test comparison using MC simulations are displayed in **Figure 4** as a two-dimensional color map with axes of variability amplitude versus the fraction of the sample which is variable versus steady. Lighter colors (indicating sample KS-test p-values closer to 1) show the simulations most resembling the data. While there is an expected degeneracy between the scale of the variability and fraction of sample exhibiting it, the analysis shows that between 30 and 100% of jets are variable, with a characteristic scale of ~ 10% in amplitude.

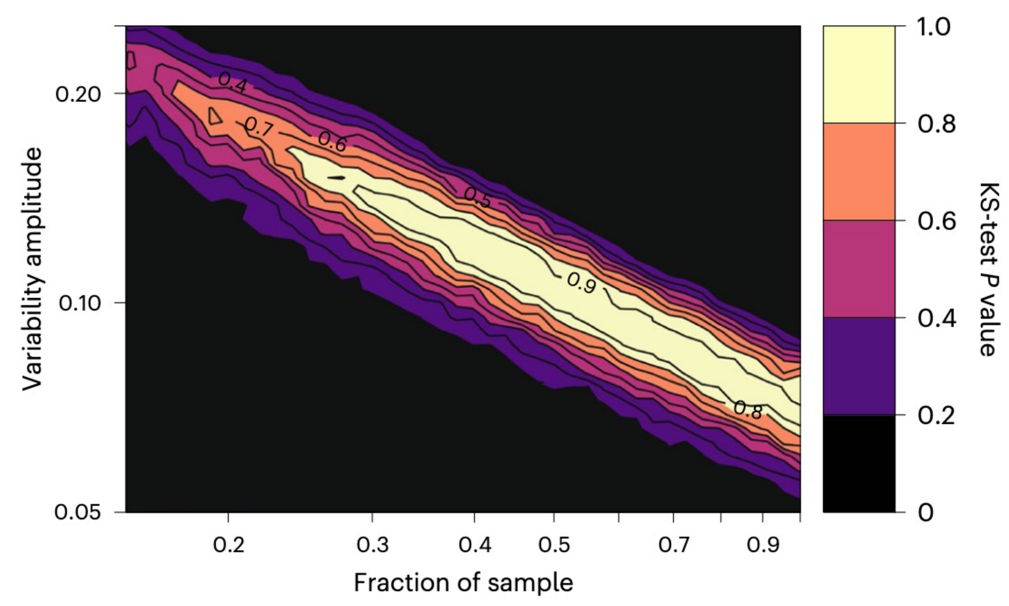


Figure 4 | Level plot showing the p-value for a KS test comparing simulated data sets to our observed single-region p-value distribution. Here we vary the simulated fraction of the population that is variable (x axis) and the amplitude of the variability for that subset (y axis). Higher KS-test P values (lighter colors) indicate closer agreement with the observed data.

What factors are associated with variability?

To test if any source characteristics were more associated with variability than others, we split the sample into two subsets and re-ran the one-sided KS test of the single-region p-value distribution against a U(0,1) distribution for each subset. The results are summarised in Table 1. For subsets where the KS-test p-value is lower than that of the full sample, the final column in these tables gives a percentage which is the probability of obtaining the lower KS-test p-value purely by chance for a subselection of size n from the full parent population. High-redshift quasars in particular appear consistent with steady emission (**Figure 5**).

Table 1 | Results of the one-sided subsample KS tests against the *U*(0,1) distribution, not adjusted for multiple comparison

Characteristic	Subset	*n*	Break	KS-test *P* value	Percentile
Jet angle	High	78	$\theta \geq 15.5°$	0.0001212	6.17
	Low	77	$\theta < 15.5°$	0.1227422	
Average source counts	Many	89	$n \geq 40$	0.0019570	
	Few	66	$n < 40$	0.0467632	
Background/source count ratio	Low	66	$\langle n_{src}/n_{bg} \rangle < 0.1$	0.0010641	
	High	89	$\langle n_{src}/n_{bg} \rangle \geq 0.1$	0.0246957	
Core dist.	Far	83	$d \geq 5''$	0.0000327	2.22
	Near	72	$d < 5''$	0.2920501	
Jet length	Long	82	$l \geq 10''$	0.0008115	
	Short	73	$l < 10''$	0.0431792	
Knot sequence	Later knots	102	—	0.0023121	
	First knots	53	—	0.0208292	
Knot type	Non-hotspot	110	—	0.0025399	
	Hotspot	45	—	0.0076676	
Radio power	Low power	60	$L_{300MHz} < 10^{43}$ erg s^{-1}	0.0000654	2.34
	High power	95	$L_{300MHz} \geq 10^{43}$ erg s^{-1}	0.1019381	
Spectral type	Broad lined	120	—	0.0000934	10.14
	Narrow lined	33	—	0.4180435	
Redshift	Low	75	$z < 0.6$	0.0000035	0.36
	High	80	$z \geq 0.6$	0.2296055	
Jet class	Not CDQ	81	—	0.0001501	7.33
	CDQ	74	—	0.1272601	
Jet class + redshifts	Not high-*z* CDQ	100	$z < 0.6$ or not CDQ	0.0000032	0.21
	High-*z* CDQ	55	$z \geq 0.6$ and CDQ	0.7034346	

CDQ, core-dominated quasar.

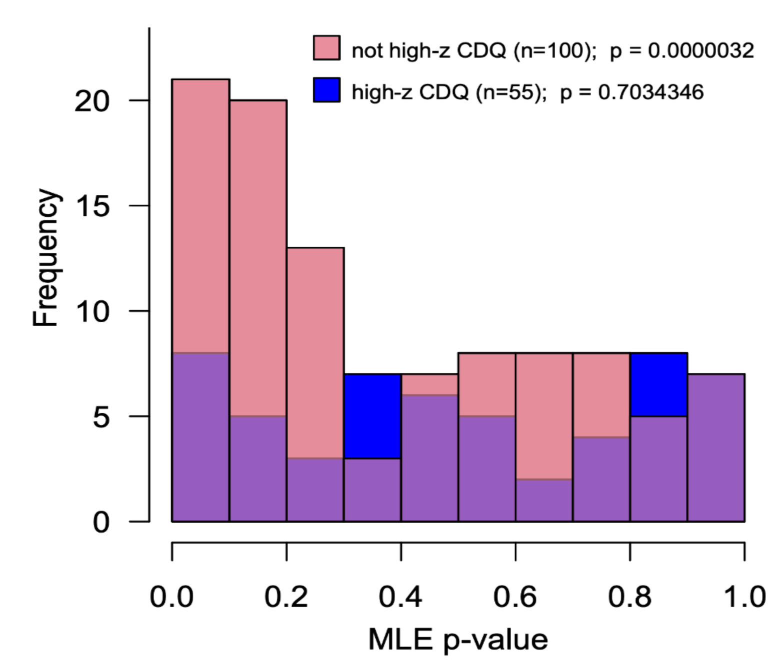
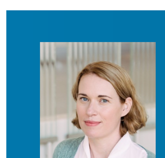


Figure 5 | Histogram of the single-region P values. In pink, the subset of sources that excludes core-dominated quasars at high redshift have a P-value distribution more discrepant from U(0, 1) than the full sample. This implies that high-redshift core-dominated quasars (blue) could represent a true non-variable population, in keeping with theoretical expectations.

Conclusions

Variability in the X-ray emission from large-scale jets on timescales of a few months–years is not compatible with the IC/CMB mechanism: the CMB is completely steady, and the electrons upscattering it are very low energy with extremely long cooling timescales, many orders of magnitude longer than the light-crossing time for the jet. Assuming a synchrotron origin, the X-rays must be emitted by very energetic multi-TeV energy electrons, where the cooling timescale is accordingly much shorter. Combined with a very small emitting volume (on the order of light-months), it is possible to produce the observed variability. Such small volumes, however, are in conflict with the typical assumption of particle acceleration which is distributed throughout the jet cross-section.



Contact:

Eileen Meyer
University of Maryland Baltimore County
meyer@umbc.edu

astro.umbc.edu

References

1. Blandford, R., Meier, D. & Readhead, A. *ARA&A* 57, 467–509 (2019). 1812.06025.
2. Chartas, G. et al. *ApJ* 542, 655–666 (2000). astro-ph/0005227.
3. Schwartz, D. A. et al. *ApJ Letters* 540, 69–72 (2000). astro-ph/0005255.
4. Hardcastle, M. J. *MNRAS* 66, 1465–1474 (2006). astro-ph/0511511.
5. Tavecchio, F., et al., *ApJ Letters* 544, L23–L26 (2000). astro-ph/0007441.
6. Celotti, A., et al., *MNRAS* 321, L1–L5 (2001). astro-ph/0008021.

This Research published in: Meyer, E. T., Shaik, A., Georganopoulos M., et al., Nature Astronomy, 29 May 2023

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