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Unveiling X-ray Jet Emission In High-Redshift Radio-Loud Quasars With No Continuous Radio Jet

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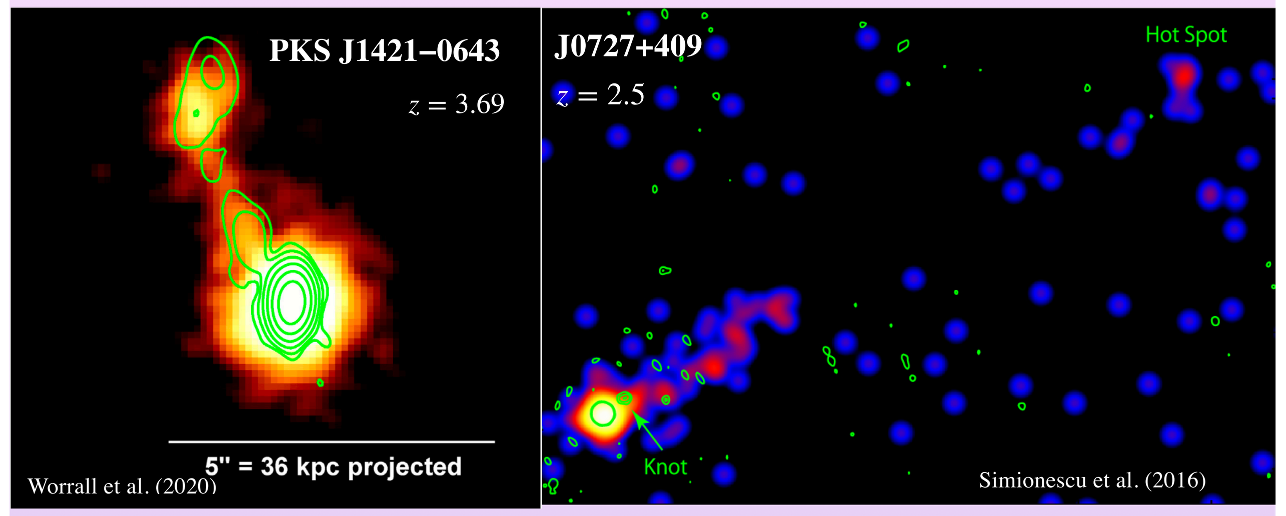
Why Study Quasar Jets?

Quasars emit relativistic jets that can transport energy from the SMBH to the inter-cluster medium (e.g., Bridle & Perley, 1984)

Chandra has observed jets up to $z > 6$, expanded our understanding of extragalactic jet power and morphology, although data for jets at $z > 3$ is sparse

Discovery of an X-ray jet at $z = 2.5$ without a corresponding radio jet provides insights into lifetimes and acceleration processes of relativistic electrons

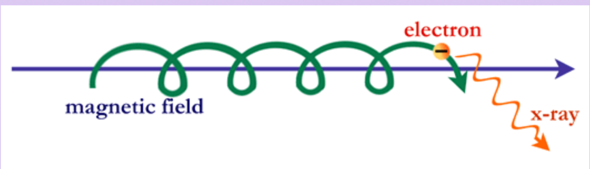


Left: PKS J1421-0643 at z=3.69 shows 36 kpc continuous X-ray jet coincident with the radio emissions (Worrall et al. 2020). Right: J0727+409 at z=2.5 shows X-ray jet of projected length ~100 kpc with only radio emission from the core & knot (Simionescu et al. 2016)

Candidate Jet X-ray Emission Mechanism

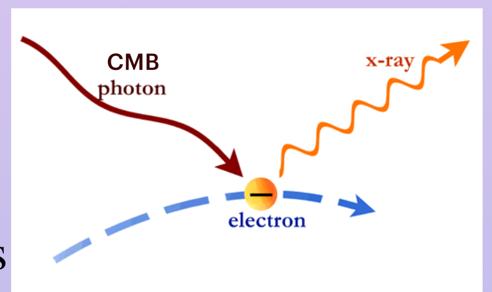
Synchrotron Interpretation :

For slower and highly magnetized jets on kpc scales



Inverse Compton of Cosmic Microwave Background (IC/CMB):

For highly relativistic jets with minimal deceleration or energy dissipation over sub-pc to kpc scales



Factors Favoring IC/CMB At High-z

- Surface brightness $\propto (1+z)^{-4}$ ↓
- CMB energy density $\propto (1+z)^{4}$ ↑
- Longer electron lifetimes producing X-ray via IC/CMB

Sample Selection

Parent Survey
Gobeille et al. (2014)
SDSS x FIRST
$S_{1.4,5\mathrm{GHz}} > 70$ mJy, $z \geq 2.5$
123 RL quasars, 61 extended radio

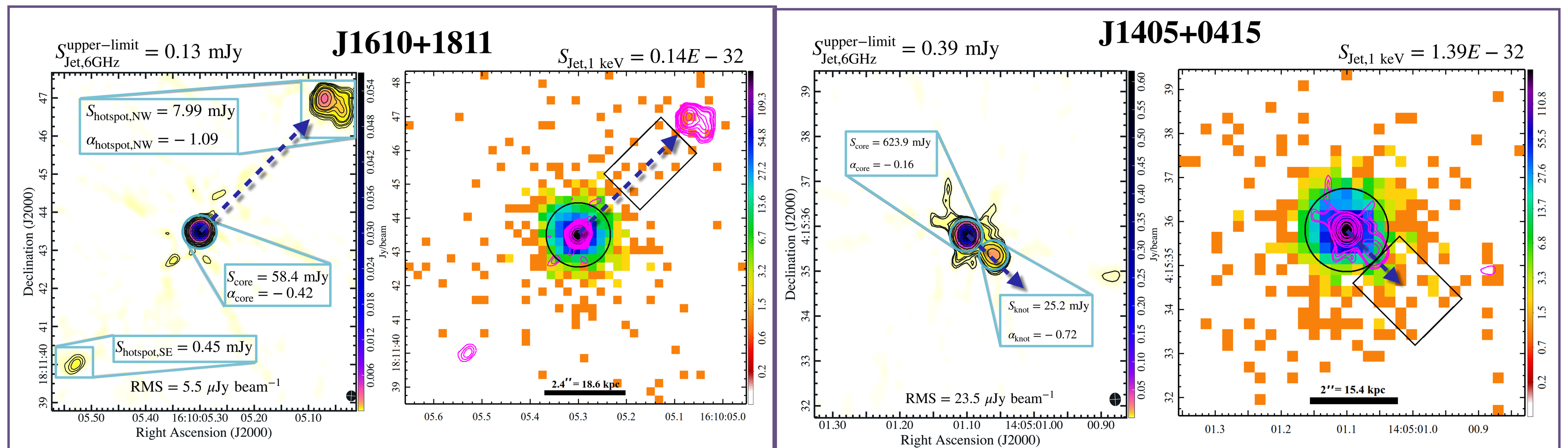
→

Selection Criteria
Excluded triple radio sources
Redshift cutoff > 3
Excluded two known X-ray sources
14 RL quasars

→

10 ks Chandra Observation
Schwartz et al. (2020)
Two X-ray Jet Candidates
J1405+0415, J1610+1811
90 ks Chandra follow-up

New VLA 6 GHz A-array Radio And Chandra X-ray Observations



(A) 6 GHz VLA **(B) 0.5-7 keV Chandra** **(C) 6 GHz VLA** **(D) 0.5-7 keV Chandra**

Figures (A) & (C) *show 6 GHz radio synthesized images with contour levels of [2√2, 3√2, 4√2, 6√2, 10, 18, 26, 30, 50, 80, 200, 400, 800] × 27.5 µJy/beam for J1610+1811 and [3√2, 4√2, 6√2, 10, 20, 40, 80, 200, 600, 1000, 2000] × 141 µJy/beam for J1405+0415, with radio emission from the core, knots, and/or hotspots marked.* ***Figures (B) & (D)*** *display ~90 ks Chandra ACIS-S images at 0.5-7 keV range are shown with 0."246 pixels to match the spatial resolution of the radio data. Both images are displayed in logarithmic scale and the color bar indicates counts per pixel. The black boxes highlight the regions of detected continuous X-ray jets. X-ray flux density unit is erg/s/cm²/Hz*

No radio emission detected from the ***continuous jet***, but ***>5σ detection of extended X-ray emission*** at PA = 315 (225) for J1610+1811 (J1405+0415), aligning with the extended radio emission

IC/CMB Jet Model & Simulations For Line Of Sight Angle

Inputs

Geometry: Cylindrical, radius ~3 kpc & lengths derived from X-ray emission
Electron Distribution: Power-law, $N(\gamma)d\gamma \propto \gamma^{-2.4}\, d\gamma$, with γ from 30 to 10^5
Fluxes: Upper limit from 6 GHz radio maps and observed 1 keV X-ray fluxes

Process

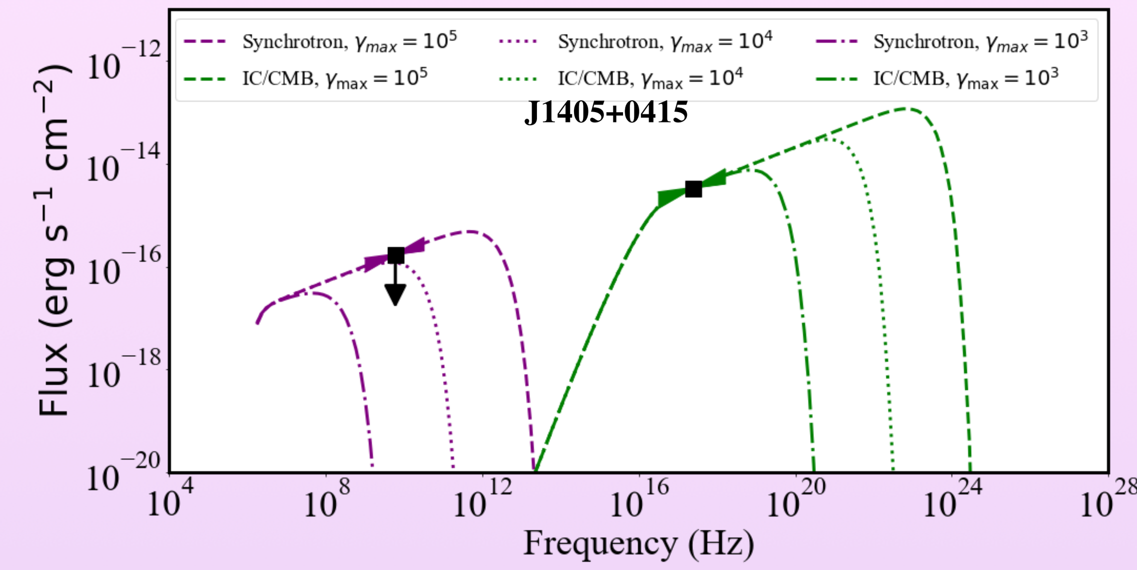
The observed radio to X-ray flux density ratio is set by the energy density ratio of the magnetic field to CMB photons. Our model iteratively determines the bulk Lorentz factor, (Γ) for various line-of-sight angles (θ), where the minimum energy magnetic field matches the field required to produce the observed flux density ratio

A Novel Method To Find θ

Integrate Murphy's (1988) probability distribution for θ from 0 to 90°
For a given Γ from the IC/CMB model, solve for θ that matches the integrated probability to a uniform distribution between 0 and 1. Repeat 10,000 times to obtain a posterior probability distribution of θ

Results From IC/CMB Model Of Jet

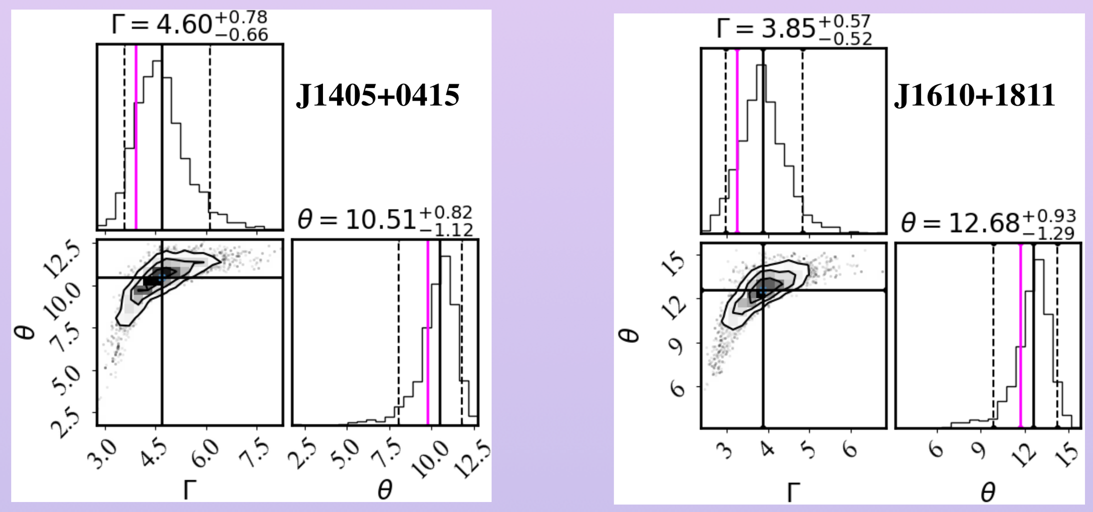
Synchrotron emission from low-energy electrons ($\gamma < 10^5$) is below the 6 GHz flux limit but can produce X-ray emission via IC/CMB



Limits on Jet Parameters from IC/CMB model

Parameters	J1405+0415		J1610+1811	
	Median	90% C.I.	Median	90% C.I.
(1)	(2)	(3)	(4)	(5)
$\theta \downarrow$	10	(3, 16)	12	(4, 19)
$\Gamma \uparrow$	4	(3, 7)	3	(2, 6)
$\delta \uparrow$	5	(5, 3)	4	(4, 2)
$\beta \uparrow$	0.96	(0.93, 0.96)	0.95	(0.91, 0.98)
B (μG) $\downarrow$	20	(15, 36)	11	(8, 20)
n_e (10^{-7}cm^{-3}) $\downarrow$	1.2	(0.6, 3.6)	0.4	(0.2, 1.1)
K.E. (10^{46}erg s^{-1}) $\downarrow$	2.8	(0.7, 28.3)	0.4	(0.1, 4.6)

Our IC/CMB model is consistent with 'JetSeT'



Two dimensional projections of the posterior probability distributions of θ and Γ for J1405+0415 (left) and J1610+1811 (right) obtained using Jets SED modeler and fitting Tool (JetSeT). The black and magenta solid lines represent the median value of the parameter from JetSet and our IC/CMB model, respectively. The black dashed line represents the 0.05 and 0.95 quantile from JetSet. ***The median values of θ and Γ predicted by our IC/CMB model are consistent with the ones predicted by JetSet within the model uncertainty***

Conclusion

We confirm detection of X-ray extended emission in J1610+1811 & J1405+0415 with $>5\sigma$ significance. Based on the radio flux upper limit for the jet, IC/CMB model predicts reasonable limits of the jet parameters

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References: Begelman, M. C., Blandford, R. D., & Rees, M. J. 1984, RvMP, 56, 255 | Gobeille, D. B., Wardle, J. F. C., & Cheung, C. C. 2014, 469 arXiv e-prints, arXiv:1406.4797 | Murphy, D. W. 1988, PhD thesis, University of Manchester, UK | Schwartz, D. A., Siemiginowska, A., Snios, B., et al. 2020, ApJ, 904, 57 | Simionescu, A., Stawarz, L., Ichinohe, Y., et al. 2016, ApJL, 816, L15 | Worrall, D. M., Birkinshaw, M., Marshall, H. L., et al. 2020, MNRAS, 497, 988