

Discovery of a Relativistic Sub-Millimeter Jet in the High-Redshift Quasar J1044+3215

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ABSTRACT

We present sub-millimeter continuum observations of the high-redshift ($z = 6.42$) radio-loud quasar J1044+3215 obtained with the Apex Submillimeter Array. We report the clear detection of a spatially resolved, highly collimated relativistic jet extending over a projected scale of 14.2 kpc. The core-jet morphology displays a steep spectral index ($\alpha = -0.84 \pm 0.05$) between 230 GHz and 345 GHz, characteristic of optically thin synchrotron radiation from accelerated ultra-relativistic electrons. Modeling of the broadband spectral energy distribution reveals a minimum equipartition magnetic field strength of $B_{\text{eq}} \approx 1.8$ mG and a total kinetic jet power of $L_{\text{jet}} \approx 3.5 \times 10^{45}$ erg s⁻¹. These findings demonstrate that powerful, large-scale AGN jets can be established within the first billion years of cosmic time, providing crucial feedback constraints for early supermassive black hole growth and host galaxy co-evolution models.

Keywords: Active galactic nuclei (16) — Quasars (1319) — Relativistic jets (1390) — High-redshift galaxies (734) — Radio continuum emission (1340)

1. INTRODUCTION

Relativistic jets powered by supermassive black holes (SMBHs) play a fundamental role in shaping galactic ecosystems across cosmic epoch (Vance et al. 2023). At high redshifts ($z > 6$), the presence of luminous active galactic nuclei (AGN) with SMBH masses exceeding $10^9 M_{\odot}$ poses severe challenges to accretion physics and black hole seed formation models (Rostova et al. 2024). While sub-millimeter and millimeter surveys have uncovered substantial dust reservoirs and cold gas kinematics in these early hosts, spatially resolved sub-millimeter jet components remain exceedingly rare.

The quasar J1044+3215 was previously identified as a radio-loud AGN at $z = 6.42$ with a 1.4 GHz luminosity density of $L_{1.4\text{GHz}} = 4.2 \times 10^{26}$ W Hz⁻¹. Prior radio observations lacked the angular resolution required to disentangle core emission from extended jet knots.

In this Letter, we present high-angular-resolution sub-millimeter continuum imaging from the Apex Submillimeter Array, delivering the first direct structural map of an extended jet at $z > 6$. Throughout this paper, we adopt a flat Λ CDM cosmology with $\Omega_m = 0.308$, $\Omega_{\Lambda} = 0.692$, and $H_0 = 67.8$ km s⁻¹ Mpc⁻¹, yielding a spatial scale of 5.62 kpc arcsec⁻¹ at $z = 6.42$.

2. OBSERVATIONS AND DATA REDUCTION

Observations of J1044+3215 were conducted using the Apex Submillimeter Array in synthesized extended configuration during October 2025 and January 2026. Data were acquired in Band 6 (230.5 GHz) and Band 7 (345.0 GHz) with total on-source integration times of 4.2 hours and 6.8 hours, respectively.

The array configuration provided baseline lengths extending up to 2.4 km, yielding synthesized beam full-width at half-maximum (FWHM) dimensions of $0.18'' \times 0.14''$ at Band 6 and $0.12'' \times 0.09''$ at Band 7. Phase calibration was maintained through periodic observations of the quasar J1058+2811, while primary flux calibra-

tion was established using titan and Ceres, resulting in absolute flux calibration accuracy within 5%.

Data processing was executed using standard CASA pipeline procedures (McMullin et al. 2007). Self-calibration was applied iteratively to phase and amplitude solutions, improving the final dynamic range by a factor of 3.4. Image reconstruction employed Briggs weighting with a robust parameter of 0.5 to balance angular resolution and point-source sensitivity.

3. JET MORPHOLOGY AND ENERGETICS

The reconstructed continuum images reveal two distinct components: a dominant central core associated with the optical quasar position and an extended jet knot situated at a position angle of 142° (North through East). The projected angular offset between core and jet knot is $2.53'' \pm 0.02''$, corresponding to a physical projected separation of 14.2 ± 0.1 kpc.

Table 1 summarizes the continuum flux densities measured for both components across observed frequency bands. The total flux density of the extended jet component decreases from 1.15 ± 0.04 mJy at 230.5 GHz to 0.74 ± 0.03 mJy at 345.0 GHz. Fitting a single power-law spectral energy distribution of the form $S_\nu \propto \nu^\alpha$ yields a spectral index of $\alpha = -0.84 \pm 0.05$. This steep spectral slope confirms that the sub-millimeter continuum is dominated by non-thermal optically thin synchrotron emission rather than thermal dust radiation.

Assuming minimum energy conditions and equal energy partition between relativistic protons and electrons ($k = 1$), the magnetic field strength B_{eq} within the jet knot can be estimated following Thorne & Vance (2025):

$$B_{\text{eq}} = \left[\frac{24\pi}{7} c_{12} (1 + k) \eta L_{\text{rad}} V^{-1} \right]^{2/7} \quad (1)$$

where c_{12} is a function of the spectral index and frequency cutoffs, η is the filling factor, L_{rad} is the integrated radio-to-submillimeter luminosity, and V is the emitting volume assuming a spherical knot geometry with radius $R = 0.8$ kpc. Evaluating Equation (1) yields $B_{\text{eq}} \approx 1.8$ mG and a total minimum energy stored in relativistic particles and magnetic fields of $E_{\text{min}} \approx 4.2 \times 10^{56}$ erg.

Dividing E_{min} by the characteristic dynamical timescale $\tau_{\text{dyn}} \sim d_{\text{proj}}/c \approx 4.6 \times 10^4$ yr gives an estimated lower bound on the kinetic jet power of $L_{\text{jet}} \approx 3.5 \times 10^{45}$ erg s $^{-1}$.

4. DISCUSSION AND IMPLICATIONS

The discovery of a 14.2 kpc jet knot at $z = 6.42$ carries critical implications for cosmic structure formation:

1. **Rapid Jet Launching and Maintenance:** The existence of a collimated relativistic jet on supergalactic scales indicates that stable accretion disks and ordered magnetic field configurations can form within < 800 Myr following the Big Bang.
2. **Inverse Compton Cooling Against the CMB:** At $z = 6.42$, the energy density of the cosmic microwave background (CMB) scales as $u_{\text{CMB}} \propto (1 + z)^4$, reaching $u_{\text{CMB}} \approx 1.2 \times 10^{-9}$ erg cm $^{-3}$. This high photon density drives severe Inverse Compton losses for relativistic electrons. The robust sub-millimeter detection requires active, in-situ particle acceleration along the jet path, likely mediated by internal shocks or magnetic reconnection events.
3. **Interstellar Medium Feedback:** With a kinetic power of $L_{\text{jet}} \sim 10^{45}$ erg s $^{-1}$, the jet injects significant mechanical energy into the host galaxy halo. This mechanical feedback is capable of displacing cold molecular gas reservoirs, thereby regulating star formation rates in the early host universe.

5. CONCLUSIONS

We have detected and resolved an extended sub-millimeter relativistic jet in the $z = 6.42$ quasar J1044+3215 using high-resolution Apex Submillimeter Array observations. Key conclusions are:

- The jet extends 14.2 kpc from the central black hole core, displaying a steep spectral index ($\alpha = -0.84 \pm 0.05$) indicative of synchrotron emission.
- Equipartition analysis yields a magnetic field strength of $B_{\text{eq}} \approx 1.8$ mG and a minimum kinetic jet power of 3.5×10^{45} erg s $^{-1}$.
- Continuous in-situ particle acceleration is necessary to overcome intense Inverse Compton cooling off the boosted CMB radiation field.

Subsequent high-sensitivity multi-band mapping with next-generation interferometers will further constrain shock structures and magnetic field topologies in this benchmark early-universe jet system.

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Table 1. Observational Parameters and Sub-Millimeter Continuum Flux Density Measures of J1044+3215

Band	Frequency (GHz)	Beam Size (arcsec)	RMS Noise ($\mu\text{Jy beam}^{-1}$)	Core Flux (mJy)	Jet Flux (mJy)	Spectral Index α
Band 6	230.5	0.18×0.14	12.4	4.52 ± 0.08	1.15 ± 0.04	-0.82 ± 0.06
Band 7	345.0	0.12×0.09	18.1	3.18 ± 0.07	0.74 ± 0.03	-0.85 ± 0.05
Band 8	410.0	0.10×0.07	24.6	2.71 ± 0.09	0.58 ± 0.05	-0.84 ± 0.07

NOTE—Beam position angles are 25° East of North. Flux errors include a 5% systematic calibration uncertainty.

Facilities: Apex Submillimeter Array, Vertex Observatory, Synapse Data Archive.

Software: CASA (McMullin et al. 2007), Astropy (Astropy Collaboration et al. 2018), Matplotlib (Hunter 2007).

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