Evolving parsec-scale radio structure in the most distant blazar known

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Blazars are a sub-class of quasars with Doppler boosted jets oriented close to the line of sight, and thus efficient probes of supermassive black hole growth and their environment, especially at high redshifts. Here we report on Very Long Baseline Interferometry observations of a blazar J0906+6930 at z = 5.47, which enabled the detection of polarised emission and measurement of jet proper motion at parsec scales. The observations suggest a less powerful jet compared with the general blazar population, including lower proper motion and bulk Lorentz factor. This coupled with a previously inferred high accretion rate indicate a transition from an accretion radiative power to a jet mechanical power based transfer of energy and momentum to the surrounding gas. While alternative scenarios could not be fully ruled out, our results indicate a possibly nascent jet embedded in and interacting with a dense medium resulting in a jet bending.
Mechanisms for the formation and rapid growth of supermassive black holes (SMBHs) in the early Universe remain debatable and have a complex connection with the evolution of their host galaxies through feedback. The discovery of quasars at redshift \( z \gtrsim 6 \) (refs. 5, 6) indicates that SMBHs as heavy as \( \sim 10^{9} \) solar masses (MW) have already existed when the Universe was at about a tenth of its current age. Spectroscopic surveys have largely enabled the discovery of high-redshift galaxies and quasars, paving the way for deeper optical, infrared and radio follow-up observations5–9. Currently there are more than 200 quasars discovered above redshift of 5.7 (ref. 7).

High-redshift blazars are useful probes of the early Universe and infrared and radio follow-up observations5

Mass of the SMBH9, blazars shed light on the cosmic evolution of

High-redshift blazars are useful probes of the early Universe11,13, active inputs for planning future surveys. This information can help to study the formation of SMBHs in the early Universe11,13 and the interaction of jets with the galactic nucleus (AGN) activity, the interaction of jets with the surrounding interstellar medium (ISM) and AGN feedback influencing the evolution of the host galaxy2.

The source J0906 + 6930 (\( z = 5.47 \)), identified as a blazar14 remains the farthest yet in its class of objects. Unravelling the structure of this high-redshift blazar requires extremely high resolution. It has a prominent pc-scale core-jet structure, unravelled by Very Long Baseline Array (VLBA) observations at 15 GHz2,15. The archival 15 GHz and new 22 GHz data obtained with the Korean VLBI network and the Japanese VLBI Exploration of Radio Astrometry (KAVa) arrays confirm a core-jet structure with a projected size of \( \sim 5 \) pc, extending to the southwest direction16.

Here, we report the measurement of proper motion and linear polarisation in the parsec-scale jet of this high-redshift blazar. We use new 15 GHz data observed with the VLBA in 2017 and 2018, archival VLBA data obtained in 2004–2005 (see details in Supplementary Table 1) and the flux densities reported by the 40 m telescope at the Owens Valley Radio Observatory (OVRO) to explore the evolution of the source morphology and its physical characteristics. The jet parameters (lower proper motion and bulk Lorentz factor) are inclined to support a less powerful jet, compared with the general blazar population. The jet interacts with the surrounding interstellar medium resulting in a jet bending and polarised emission.

**Results**

The new 15-GHz VLBA images are shown in Fig. 1d, e and the archival images in Fig. 1a–c. The noise in the image from the 2017 observation is a factor of 7–16 lower than those obtained during 2004–2005. All image parameters (beam size, peak brightness and rms noise) are presented in Supplementary Table 2. The peak brightness of the 2017 and 2018 images is \( \sim 3 \) times lower than 13 years ago, consistent with the declining flux density as indicated from the long-term 15 GHz light curve based on single-dish monitoring at the OVRO (see Supplementary Fig. 1).

A compact core-jet structure is present in all images. The shape of the elliptical Gaussian model indicates that the core region (C) is a blend of the optically thick (at 15 GHz) jet base and an inner section of the optically thin jet. The major to minor axis ratio of C ranges between 3.7 and 13.5 with a northeast–southwest elongation. The jet component J1 is \( \sim 0.9 \) mas away from the core at a position angle of \( \sim 138^\circ \). In the highest-resolution 2005 image16 and the new 2017 image, a sharp (\( > 90^\circ \)) jet bending is seen from the southwest to the south at the location of J1. The fainter component J2 is at the end of the pc-scale jet, about 1 mas south of the core. The same bent jet morphology is seen at lower frequencies17, up to \( \sim 2 \) mas from C.

Apparently abrupt changes in jet direction on pc scales in blazars are frequently observed. In most cases this implies a slight change of direction in the jet which points very close to our LOS. The jet bending itself may indicate a low-pitch angle helical motion18, like, e.g., in the well-studied blazar 1156 + 295 (ref. 19). Alternatively, the jet bending may also result from interaction with massive clouds in the ISM, e.g. dense clouds in the broad or narrow line regions20,21. In the present case of J0906 + 6930, we find no indication for helical motion, for example, there is no noticeable variation in the core position angle or in the shape of the optically thick jet base (i.e. the fitted core component in Table 1), and there are no significant periodic variations seen in the light curve (Supplementary Fig. 1). There is however support for possible jet–ISM interaction, evidenced by the relatively high levels of linear polarisation observed near the jet bending (see discussion below). The density contrast between the material in the jet and that external to it is \( \gtrsim 9 \) (see Methods: jet and ISM properties), thus suggesting a relatively lighter jet susceptible to interaction and bending owing to a relatively denser medium. Assuming a momentum balance across the jet–ISM interaction, the ISM number density is estimated to be \( n_{\text{ISM}} \geq 26.6 \text{ cm}^{-3} \).

The position of J1 (projected distance \( \sim 5.3 \text{ pc} \) away from the core) is nearly stationary between 2004 and 2018, consistent with a jet beam encountering dense surrounding ISM. This is also supported by the increasing flux density at J1, which represents a standing shock where the material and magnetic fields near the jet...
Table 1 Model fitting parameters.

| Epoch (yyyy mm dd) | Comp | $S_{\text{total}}$ (mJy) | $D_{\text{maj}}$ (mas) | $D_{\text{min}}$ (mas) | $\varphi$ (°) | $R$ (mas) | PA (°) | $T_B$ ($\times 10^{10}$ K) |
|-------------------|------|----------------------|----------------------|----------------------|----------------|-----------|---------|-----------------------------|
| (1)               |      |                      |                      |                      |                |           |         |                             |
| 2004 02 27        | C    | 115.6 ± 6.4          | 0.206 ± 0.005        | 0.041 ± 0.001        | 40.9 ± 0.9    | -         | -       | 47.5 ± 3.0                   |
|                   | J1   | 7.2 ± 0.7            | 0.396 ± 0.051        | -                     | -              | 0.825 ± 0.068 | 222.2 ± 1.1 | -                           |
| 2004 11 22        | C    | 127.3 ± 6.6          | 0.269 ± 0.002        | 0.065 ± 0.002        | 28.1 ± 0.1    | -         | -       | 24.4 ± 1.5                   |
|                   | J1   | 8.7 ± 0.8            | 0.279 ± 0.027        | -                     | -              | 0.906 ± 0.064 | 225.0 ± 0.3 | -                           |
| 2005 03 22 & 15   | C    | 122.7 ± 6.4          | 0.209 ± 0.001        | 0.067 ± 0.002        | 55.3 ± 0.1    | -         | -       | 31.0 ± 1.8                   |
|                   | J1   | 8.4 ± 0.6            | 0.267 ± 0.007        | -                     | -              | 0.944 ± 0.052 | 224.7 ± 0.2 | -                           |
|                   | J2   | 1.9 ± 0.3            | 0.321 ± 0.053        | -                     | -              | 1.290 ± 0.061 | 179.8 ± 1.3 | -                           |
| 2017 09 11        | C    | 43.4 ± 2.3           | 0.260 ± 0.001        | 0.032 ± 0.001        | 49.4 ± 0.1    | -         | -       | 18.0 ± 1.1                   |
|                   | J1   | 20.4 ± 1.1           | 0.291 ± 0.011        | -                     | -              | 0.814 ± 0.049 | 222.2 ± 0.1 | -                           |
|                   | J2   | 1.0 ± 0.1            | 0.270 ± 0.033        | -                     | -              | 1.568 ± 0.053 | 184.6 ± 0.1 | -                           |
| 2018 01 31        | C    | 41.8 ± 2.2           | 0.249 ± 0.004        | <0.034               | 52.2 ± 1.3    | -         | -       | >17.1                        |
|                   | J1   | 18.0 ± 1.0           | 0.170 ± 0.001        | -                     | -              | 0.801 ± 0.071 | 228.2 ± 0.1 | -                           |
|                   | J2   | 1.4 ± 0.2            | 0.444 ± 0.079        | -                     | -              | 1.435 ± 0.076 | 184.8 ± 0.9 | -                           |

Parameters are derived from modelled Stokes LL images. Column (1) presents the observation epoch. Column (2) gives the label of the VLBI component. Column (3) presents the integrated flux density of all VLBI components. Columns (4) to (5) give the major and (in case of ellipticals) the minor axis sizes (FWHM) of the fitted Gaussian models. Column (6) is the position angle of the major axis of Gaussian, measured from north to east. The data from 22 March 2005 and 15 May were combined before model fitting. Columns (7) and (8) give the radial distance of components with respect to the core, and the position angle measured from north to east. Column (9) lists the calculated brightness temperature of the core. For the unresolved core, a maximum size is estimated, thus the lower limit of $T_B$ is given.

Fig. 2 Linear polarisation image (coloured scale) of J0906 + 6930. The images are derived from the 15-GHz VLBA observation on 31 January 2018. The core is denoted by C and jet components by J1 and J2. The contours represent Stokes I intensity, same as Fig. 1e. The coloured scale denotes the fractional polarisation. The core region is weakly polarised. This is the only polarisation component. The core region is weakly polarised. This is the only polarisation fraction is ~10%, and the peak polarised intensity is ~0.6 mJy beam$^{-1}$, is about 0.8 mas southwest of the total intensity core. The maximum fractional polarisation is ~10% appearing at the southernmost of the polarised component. The core region is weakly polarised. This is the only polarisation measurement in a radio-loud quasar at redshift $>5$ so far.

The implications of AGN jet activity on SMBH growth in the early Universe and additional alternative scenarios enabling the jet structure are discussed in Methods: black hole mass. To check the latter picture, further high-sensitivity radio interferometric observations are necessary to search for relic emission structure on 100 mas scales.

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At $z > 4.5$, about 50 quasars have been detected in radio bands with 30 of them being VLBI imaged\(^5\). As the sources are mostly dominated by compact single components with flux densities <20 mJy (at GHz observing frequencies), proper motion measurements face challenges owing to the relative scarcity, faintness and a requirement for long time gaps between epochs for a definitive estimate due to cosmological time dilation. Successful measurements have been only made for two $z > 4$ blazars with the European VLBI Network (EVN) using only two epochs. These include J1026 + 2542 ($z = 5.27$) with a proper motion of 3.3–14.0 c over 7 years\(^29\) and J2134–0419 ($z = 4.33$) with a proper motion of 4.1 ± 2.7 c over 16 years\(^30\). The compact and bright jet in J0906 + 6930 makes it suitable for the study of jet kinematics. Combining the archival and new data, the proper motion of J1 is $-0.006 ± 0.004$ mas yr\(^{-1}\) (−0.8 ± 0.5 c, Fig. 3), consistent with a scenario involving jet–ISM interaction and the subsequent jet bending. The separation of component J2 shows a visible increase from 1.27 mas in 2005 to 1.58 mas in 2017/2018. The apparent proper motion of J2 is $0.019 ± 0.006$ mas yr\(^{-1}\) (2.5 ± 0.8 c, Fig. 3). These are the preliminary measurements for a $z > 4.5$ blazar based on data spanning more than two epochs and are consistent with (much lower than) a maximal proper motion of 0.09 mas yr\(^{-1}\) expected in a highly beamed jet in an accelerated cosmological expansion (see Methods maximum proper motion). For a sample of 122 relatively lower-redshift ($z = 0.1–3$) radio-loud AGN, the median jet proper motion peaks at $\leq 0.018$ c\(^34\), with the low synchrotron peaked sources indicating the fastest speeds (upto ~40 c) and high Doppler boosted teraelectronvolt (TeV) $\gamma$-ray emission. Although the estimate for J0906 + 6930 is consistent within the statistical expectation, the apparent jet speed is significantly lower than the expected value for a low synchrotron peaked blazar.

Doppler beaming in the relativistic jet can cause the core brightness temperature ($T_B$) to exceed the theoretical limits set by equipartition between the kinetic and magnetic energy densities, assumed to be $T_{B,eq} = 5 \times 10^{10}$ K\(^32\). The $T_B$ of the J0906 + 6930 core is $30.2 ± 4.0 \times 10^{10}$ K with a consequent Doppler factor $\delta = T_B/T_{B,eq}$ of 6.1 ± 0.8 (see Methods Doppler boosting parameters). From the inferred apparent velocity and Doppler factor, the bulk Lorentz factor $\Gamma = 3.6 ± 0.5$ and inclination angle towards the observer LOS $θ = 6.8° ± 2.2°$. These values are consistent with estimates from the parametric modelling of the spectral energy distribution\(^37\). The lower Lorentz factor and slower jet component are consistent with the less powerful nature of the J0906 + 6930 jet (jet/Eddington luminosity ~0.004, see Methods: jet and ISM properties). The relatively less powerful jet in addition to clues from the radio spectrum and polarisation point to its possible nascent nature. A prominent disk emission is inferred from the modelling of the spectral energy distribution of this and three other high-$z$ blazars\(^37\). This coupled with a relatively less powerful jet luminosity marks a possible transition in this source between the accretion or quasar mode and the onset of the jet or radio mode. In the former, the accretion energy can radiatively drive (momentum transfer) surrounding gas to galactic scales, and in the latter, a powerful jet can transfer mechanical energy acting to heat up the gas at galactic and cluster scales\(^2\).

The present VLBI data thus characterise J0906 + 6930 as a high-redshift blazar with a nascent jet embedded in a dense medium causing the pc-scale jet–ISM interaction and the consequent jet bending. These represent the initial results of ongoing investigations on high-resolution imaging of a sample of high-redshift blazars. Further simultaneous multi-frequency VLBI observations can help constrain the magnetic field strength and electron density from Faraday rotation measurements. The next generation VLBI facilities (e.g. Square Kilometre Array VLBI programme\(^33\)) are more sensitive to detect much weaker high-redshift blazars, thus advancing our understanding of the co-evolution of SMBHs and host galaxies in the early Universe.

**Methods**

**VLBI observations.** The compact prominent jet and an elapsed time longer than 10 years since the earlier observations make J0906 + 6930 a promising source for continued monitoring of the evolution of the jet structure. We additionally compiled and reduced archival VLBA data in this analysis. The observational setup for each observation is presented in Supplementary Table 1.

We conducted VLBA 15 GHz observations on 11 September 2017 and 31 January 2018. All ten VLBA telescopes were requested in the proposals BZ068 and BZ2071. However, due to unfavourable weather conditions and maintenance time, the Saint Croix (SC) telescope did not participate in the observations, resulting in relatively lower resolution in east–west direction in the 2017 and 2018 images compared to those obtained from the full VLBA in 2004. To enable a complete analysis of the pc-scale jet evolution in J0906 + 6930, we obtained all available 15 GHz VLBA data from the NRAO Archive (https://archive.nrao.edu/).

For the BZ068 observation, the data were recorded in four baseband channels, each with 64 MHz bandwidth. Each of the left-handed circular polarisation (LCP) and right-handed circular polarisation (RCP) occupies two channels. A 2-bit sampling resulted in a total data rate of 1 gigabit per second (Gbps). Phase referencing was not required as the source J0906 + 6930 itself was bright and compact enough to be used for fringe fitting. Except for a few scans which were used on the fringe finder (NRAO 150 and 3C 84) in the beginning and end of the observation run, the on-source time was about 400 min. The BZ068 observation thus led to a vast improvement in image quality (lowest image noise) compared to previous VLBA observations.

The main goal of the subsequent BZ2071 observation was the detection of the linear polarisation in J0906 + 6930. The observation was carried out in full polarisation mode. The radio galaxy 3C 84 was used for instrumental polarisation calibration, and the quasar NRAO 150 for fringe searching and bandpass calibration. The recording settings are similar to those of BZ068 except that four 128-MHz baseband channels were used, resulting in a total data rate of 2 Gbps, twice that of BZ068. After observation, both datasets were correlated at the National Radio Astronomy Observatory in Socorro, USA, using the DIFX software correlator\(^4\). The post calibration and imaging were carried out at the China SKA Regional Centre prototype\(^35\).

**Data reduction.** The correlated visibility data were imported into the NRAO Astronomical Image Processing System (AIPS) software package\(^36\) for amplitude and phase calibration. We applied the standard calibration procedure of AIPS. The AIPS task APICAL was performed to calibrate the visibility amplitudes, using the antenna gains and system temperatures measured at each station during the observation. The atmospheric opacity was estimated based on the weather information recorded at each station and accounted for. The instrumental delay and global phase errors were then calibrated using the FRING task. This included a manual fringe fitting using NRAO 150 (~10 ly at this frequency in this epoch) as a reference to determine the delay offsets and phase errors between different subbands, and for application the solutions to all antennas. This was followed by running the global fringe fitting including all data to calculate and remove the global phase errors. Over 98% good solutions were achieved for both datasets.

Then, the antenna-based bandpass functions were solved from the NRAO 150 data by using the task RPASS and applied to the visibility data. The bandpass shape across the broad 128–256 MHz baseband is corrected resulting in an increased dynamic range (the ratio of image peak to noise).

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**Fig. 3 Radial distance of J1 and J2 as a function of observing time.** The straight lines (blue line for J1 and red line for J2) represent a linear regression fit to infer the jet proper motion. The denoted error bars on each point are the 1σ errors (see Table 1). That gives $μ(J1) = −0.006 ± 0.004$ mas yr\(^{-1}\), and $μ(J2) = 0.019 ± 0.006$ mas yr\(^{-1}\).
The calibrated data were averaged in each subband (each 64 MHz wide) and in time (2 s) and exported to external FITS files using the task SPLIT. The resulting single-source data file was imported into the Caltech Difmap package to further calibrate residual phase errors. The hybrid mapping process consisted of several iterations of CLEAN and self-calibration. The final image was obtained after a few iterations of phase and amplitude self-calibrations, repeated by gradually reducing the solution intervals from 8 h to 1 min. Iterations of CLEAN and self-calibration were carried out until the signal-to-noise ratio in the image was below 5σ. After self-calibration, the Stokes I, Q and U components were separately imaged. The Stokes Q and U images were then combined to create the polarised intensity image using the AIPS task COMB, shown in Fig. 2. The new VLBA measurements are consistent with the single-dish flux densities (the inset of Supplementary Fig. 1). This indicates that the integrated radio emission is dominated by the pc-scale compact core. The dimming of the core and the brightening of J1 in 2017 and 2018 (in comparison to 2004 and 2005) possibly originates from the propagating shock (post the 2011 flare) interacting with the ISM.

Model fitting and error estimation. After self-calibration, the modellisation method (in Difmap) was used to fit the visibilities (at all epochs) with Gaussian brightness distributions. The positional Gaussian rms used to fit to the core, while circular ones are used for the jet. In order to avoid positional and intensity offsets between LL and RR polarisations (a possible tiny difference), for the model fitting we used only LL cross-correlation products.

The fitted Gaussian models are shown as elliptical or circular shapes in Fig. 1. In the 2004 epochs, two components were detected: the core (C) and a southwest jet component (J1). Due to the improved sensitivity and better north–south (u,v) coverage, one more jet component J2 was detected at about 1.5 mas south of the core in the other three epochs. The core was unresolved on 31 January 2018, and its minor axis size was estimated as an upper limit by considering the restoring beam size and noise-to-level ratio. This resulted in a high-resolution image with excellent (u,v) coverage in both N–S and E–W directions. This and the resulting improved sensitivity enabled the detection of the weak J2 jet component (see Fig. 1c), which was earlier not possible. All parameters including beam properties, peak brightness and noise rms for each image are presented in Supplementary Table 2.

Radio light curve. The source has been monitored by the Owens Valley Radio Observatory 40-m telescope monitoring programme at 15 GHz from 2009. This enabled the verification of the amplitude calibration of the 15-GHz VLBA data. In Supplementary Fig. 1 we plot the light curve together with our VLBA measurements in the 2017 and 2018 epochs. The new VLBA measurements are consistent with the single-dish flux densities (the inset of Supplementary Fig. 1). This indicates that the integrated radio emission is dominated by the pc-scale compact core. The dimming of the core and the brightening of J1 in 2017 and 2018 (in comparison to 2004 and 2005) possibly originates from the propagating shock (post the 2011 flare) interacting with the ISM.

Doppler boosting parameters. The brightness temperatures of the VLBI core $T_b = 1.22 \times 10^{12} \frac{S}{D_{maj}D_{min}v^2}(1 + z)K$. (1) where $S$ is the flux density (Jy) at the observing frequency $\nu$ (GHz), $D_{maj}$ and $D_{min}$ are the major and minor axis sizes of a Gaussian model (mas), and $z$ is the redshift.

The inverse Compton catastrophe prevents the synchrotron brightness from exceeding a threshold of $10^{12}$ K. An energy equipartition between magnetic fields and relativistic particles in a synchrotron radio source sets a lower maximum brightness temperature of $10^{13}$ K, which is rapidly expected. The $T_b$ of a radio jet can be attributed to Doppler boosting of the relativistic jet beam. Using $T_b = \delta \Gamma T_{\text{iso}}$ (2) where $\delta = \left(1 - (1 - \beta \cos \theta)^{-1}\right)$ is the Doppler factor, $\Gamma$ is the bulk Lorentz factor and $\beta$ is the jet bulk speed (in units of $c$), we obtain $\delta = 6.1 \pm 0.8$. The bulk Lorentz factor $\Gamma$ and the viewing angle of the jet with respect to the observer LOS $\theta$ are

\[
\frac{\Gamma^2}{\Gamma^2 - 1} = \frac{2}{\tan \theta} + \frac{\beta^2}{\beta^2 + 1} - 1.
\]

With a jet apparent transverse speed $\beta_{app} = (2.5 \pm 0.8)c$ and $\delta = 6.1 \pm 0.9$, we obtain $\Gamma = 3.6 \pm 0.5$ and $\theta = 6.8^\circ \pm 2.2^\circ$. These values are consistent with the parametric fitting of the spectral energy distribution, where $\delta = 9.2^\circ$ and $\theta \leq 9.6^\circ$ were obtained.

Polarisation calibration. The VLBA observing project BZ071 presented in this paper was designed primarily as the preliminary exploratory attempt to detect a pc-scale polarised emission from the source. As the observing period was only 2 h, the primary focus was on inferring the intensity and the location of the polarised emission; calibration of absolute electric vector position angle (EVPA) was not attempted since it would decrease already short total exposition on the target source. The unpolarised source 3C 84 was used as the instrumental polarisation (so-called D-term) calibrator.

The correlated visibilities were then imported into AIPS to calibrate the amplitudes and phases of the data, with further details as described previously in Methodic data reduction. Additional steps included calibration of the RCP–LCP phase and delay offsets, and determination of the D-term of each telescope. The broadband width of 256 MHz makes it difficult to correct the delay offsets in the RL and LR polarisations using the task RL-DLY. To deal with this issue, two 128-MHz intermediate frequency channels (IFs) were first divided into eight 32-MHz sub-IFs using the task MORIF. Then we run the CROSSPOL procedure to check and calibrate the RCP–LCP delay offsets. Additional details are presented in the NRAO AIPS memo 79 (ref. 41). The AIPS task LPCAL was then used to determine the D-terms using the self-calibrated source model of 3C 84.
We also estimate the Doppler factor from the variability of radio flux density\textsuperscript{15,46}. The monitoring data at 15 GHz from the OVRO 40-m telescope\textsuperscript{42} is used for calculating the variability brightness temperature ($T_{\text{var}}$). We modelled the flare with a Gaussian function:

$$S(t) = A \exp \left( -\frac{t-t_0}{\Delta t} \right)^2 + B,$$

where $S(t)$ is the source flux density (Jy), $t$ is the observation time (days), $B$ is the constant noise background (Jy), $t_0$ is the peak time (days) and $\Delta t$ is the characteristic flare rise timescale (days). We used a least-squares fit to estimate the Gaussian parameters, $t_0 = 20$ May 2012, $\Delta t = 847$ days, $A = 0.149$ Jy, $B = 0.061$ Jy. The fitted parameters give a variability brightness temperature, $T_{\text{var}} = 5.7 \times 10^{12}$ K.

The corresponding Doppler factor is $\delta_{\text{var}} = \sqrt{\frac{4.8}{\pi t_0}}$. This value is consistent but marginally lower than that derived from the above VLBI model fitting.

**Maximum proper motion.** The proper motion can be expressed as

$$\mu = \beta J_{\text{gal}} \frac{c}{D_{\text{proj}}},$$

where $\beta$ is the transverse jet speed, $a = (1+z)^{-1}$ and $D_{\text{proj}}$ is the angular size distance. This can be approximated in terms of the Hubble distance $c/H_0$ as\textsuperscript{47}

$$D_{\text{proj}} = \frac{c}{H_0} \frac{a}{g(a)}$$

where

$$g(a) = \left( 1 - a \right)^{\frac{1}{2}} + 0.2278 + 0.0271 \frac{1-a}{\left( 1 + a \right)^{0.0158}} + \frac{0.312}{\left( 1 + a \right)^{0.0158}}.$$ (7)

Using Eqs. (6), (7) and $\beta = \Gamma \beta_{\text{jet}}$ (for an extremely beamed jet) in Eq. (5), the maximal proper motion

$$\mu_{\text{max}} = \frac{H_0}{\beta_{\text{jet}} g(a)}$$

for $z = 5.47$ and $\beta = 1$.

**Black hole mass and jet activity.** The previous black hole mass estimate of $M_{\text{BH}} = 4.2 \times 10^{9} M_{\odot}\textsuperscript{2}$ is in tension with the inferred observational signatures of the source resembling a high-frequency peakier, which typically have moderately lower masses in the range $10^{7.5} - 10^{9} M_{\odot}\textsuperscript{48}$.

The earlier estimates are based on scaling relations relevant to non-jetted quasars. However, the employed luminosity requires to be Doppler beaming corrected for a jetted quasar\textsuperscript{49}.

For the blazar J0906+6930, comparing the scaled broad line region (BLR)radius $r_{\text{BLR}} = (5.8 \times 10^{14})$ cm\textsuperscript{15} [Equation 15] with $r_{\text{BLR}} = (9.54 \times 10^{14})$ cm [Equation 15], resulting in $L_{\text{BLR}} = (2.6 \times 10^{46})$ erg s\textsuperscript{-1} [Equation 15]. Using this in the revised scaling relation $m_{\text{BLR}} = 3.26 \times 10^{3} \left( \frac{L_{\text{BLR}}}{10^{46} \text{ erg s}^{-1}} \right)^{1/5}$ [Equation 15], which is consistent with the above expectation from the population of sources. The lower mass and a similarity to a young AGN indicate the ongoing evolution of the black hole\textsuperscript{50}, with feedback transitioning from accretion dominated (radiative) to the onset of the jet (momentum) driving possibly resulting in a black hole

epoch\textsuperscript{15}. The average monochromatic radio power of the core-jet,

$$P_{\text{rc}} = 4\pi D_{\text{proj}}^2 S_{\text{rc}}(1+z)^{-1} \cdot 10^{-23} \text{erg s}^{-1}.$$

With a luminosity distance $D_{N} = 53.66 \text{ Gpc}$ ($z = 5.47$ for J0906+6930) obtained using CosmoCalc\textsuperscript{58}, $S_{\text{core,15GHz}} = 90.94 \pm 5.18$ mJy and the above $a = 0$, $L_{\text{radio}} \approx \varepsilon_{\text{15GHz}} P_{\text{core,15GHz}} = (7.28 \pm 0.42) \times 10^{43}$ erg s\textsuperscript{-1}. A standard ACDM cosmological model with $H_0 = 70 \text{ km} \text{ s}^{-1} \text{ Mpc}$, $\Omega_m = 0.73$ and $\Omega_{\Lambda} = 0.27$ was used. The radiative and kinetic contributions to the jet luminosity $L_{\text{jet}}$ are related to the radio luminosity by the empirical relations\textsuperscript{59}

$$\log L_{\text{jet}} \approx (12 \pm 2) \cdot (0.75 \pm 0.04) \log L_{\text{radio}}.$$ (10)

The jet luminosity is taken as the addition of the radiative and kinetic contributions and is $L_{\text{radio}} = 2.8 \times 10^{46}$ erg s\textsuperscript{-1}, and is $2.2 \times 10^{43}$ erg s\textsuperscript{-1} using $a = 6.0$ as inferred in Appendix F. This is $-0.02 \text{ L}_{\text{Edd}}$, where $\text{L}_{\text{Edd}} = (1.3 \times 10^{47}) \text{ erg s}^{-1} m_{\text{BH}}$ is the Eddington luminosity and using $m_{\text{BH}} = 4.4 \times 10^{9}$ as inferred from Appendix H.

It must be noted that the empirical relations have a large scatter mainly due to the diversity in the sources constituting the inference, ranging from radio AGN to X-ray binaries, and having to properly account for spectral state transitions, variability and systematics from comparison of data from different databases\textsuperscript{59}. The uncertainty on the jet power may thus be underestimated.

Under conditions of an ambient ISM (non-relativistic), the momentum flux balance between the jet and the ISM\textsuperscript{60}

$$L_{\text{jet}} \approx \frac{P_{\text{ISM}} \Gamma^2 c^2 A_{\text{th}}}{\beta_{\text{jet}}^2}$$

for $z = 5.47$ and $\beta = 1$.

**Data availability**

All data used in this study are public and can be accessed through the different data archives of the various instruments. NRAO VLBA archive: https://archive.nrao.edu/ archive/archive.jsp, OVRO archive: http://wwwastro.caltech.edu/ovroblazar/data/data_page.html?data_query. The authors can provide data supporting this study upon request.

**Code availability**

Upon reasonable request the authors will provide all code supporting this study.

Astronomical Image Processing System (AIPS) software can be found at http://www.aips.nrao.edu/index.shtml. Difmap software can be found at ftp://ftpastro.caltech.edu/pub/difmap/.

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**References**

1. Volonteri, M. The formation and evolution of massive black holes. Science 337, 544–547 (2012).

2. Fabian, A. C. Observational evidence of active galactic nuclei feedback. Ann. Rev. Astron. Astrophys. 50, 455–489 (2012).
3. Fan, X. et al. The discovery of a luminous z = 5.80 quasar from the Sloan Digital Sky Survey. Astron. J. 120, 1167–1174 (2000).

4. Fan, X. et al. A survey of z > 5.8 quasars in the Sloan Digital Sky Survey. I. Discovery of three new quasars and the spatial density of luminous quasars at z ~ 6. Astron. J. 122, 2833–2849 (2001).

5. Coppi, N. et al. On the nature of bright compact radio sources at z > 4.5. Mon. Not. R. Astron. Soc. 463, 3260–3275 (2016).

6. Baloković, M. et al. The past 10 Gyr of Synthesis Imaging II. vol. 186 of Astronomical Society of the Pacific Conference Series, San Francisco, 301 (2011).

7. Listner, M. et al. MOJAVE: X. Parsec-scale AGN jet kinematics. analysis based on 19 years of VLBA observations at 15 GHz. Astron. J. 152, 12 (2016).

8. Cotton, W. D. Polarization calibration of VLBI data. NRAO AIPS Memo 79, 57–77 (1979).

9. An, T. & Baan, W. A. The dynamic evolution of young extragalactic radio nuclei. Mon. Not. R. Astron. Soc. 405, 367–390 (2010).

10. Volonteri, M., Haardt, F., Ghisellini, G. & Della Ceca, R. Blazars early Universe Mon. Not. R. Astron. Soc. 416, 216–224 (2011).

11. Caccianiga, A. et al. The space density of z > 4 blazars. Mon. Not. R. Astron. Soc. 484, 204–217 (2019).

12. Tanaka, T. & Haiman, Z. The assembly of supermassive black holes at high redshifts. Astrophys. J. 783, 35 (2019).

13. Frey, S., Paragi, Z., Fogasy, J. O. & Gurvits, L. I. The dynamic evolution of young extragalactic radio nuclei. Mon. Not. R. Astron. Soc. 405, 367–390 (2010).

14. Romani, R. W., Sowards-Emmerd, D., Greenhill, L. & Michelson, P. Q0906+6930: a radio-loud quasar in the early universe. Mon. Not. R. Astron. Soc. 468, 69–76 (2017).

15. Frey, S., Titov, O., Melnikov, A. E., de Vicente, P. & Shu, F. High-resolution radio imaging of two luminous quasars beyond redshift 4.5. Astron. Astrophys. 618, A68 (2018).

16. Conway, J. E. & Murphy, D. W. Helical jets and the misalignment distribution of parsec-scale AGN jet cores. Mon. Not. R. Astron. Soc. 473, 3638–3660 (2018).

17. Greisen, E. W. In Information Handling in Astronomy—Historical Views (ed Heck, A.) 109–125 (Springer, 2003).

18. Shepherd, M. D. Difmap: an interactive program for synthesis imaging. In (eds Hunt, G. & Payne, H.) Astronomical Data Analysis Software and Systems VI, vol. 125 of Astronomical Society of the Pacific Conference Series, San Francisco, 77 (1997).

19. Kovalev, Y. Y. et al. Sub-milliarcsecond imaging of quasars and active galactic nuclei. IV. Fine-scale structure. Astron. J. 130, 2473–2505 (2005).

20. Fomalont, E. B. Image analysis. In (eds Taylor, G. B., Carilli, C. L. & Perley, R. A.) Synthesis Imaging II, vol. 186 of Astronomical Society of the Pacific Conference Series, San Francisco, 301 (2011).

21. Listner, M. et al. MOJAVE: X. Parsec-scale AGN jet kinematics. analysis based on 19 years of VLBA observations at 15 GHz. Astron. J. 152, 12 (2016).

22. Cotton, W. D. Polarization calibration of VLBI data. NRAO AIPS Memo 79, 57–77 (1979).

23. Deller, A. T. et al. DiFX-2: a more flexible, efficient, robust, and powerful software correlator. Publ. Astron. Soc. Pac. 123, 275 (2011).

24. An, T., Wu, X.-P. & Hong, X. Y. SKA data take centre stage in China. Nat. Astron. 3, 1030–1032 (2019).

25. Greisen, E. W. In Information Handling in Astronomy—Historical Views (ed Heck, A.) 109–125 (Springer, 2003).

26. Readhead, A. C. S. Equipartition brightness temperature and the inverse Compton catastrophe. Astrophys. J. 426, 51–59 (1994).

27. Paragi, Z. et al. Very long baseline interferometry with the SKA. In Proc. Advancing Astrophyics with the Square Kilometre Array, Proceedings of Science, PoS (AASKA14) 143 (2015).

28. Deller, A. T. et al. DiFX-2: a more flexible, efficient, robust, and powerful software correlator. Publ. Astron. Soc. Pac. 123, 275 (2011).

29. An, T., Wu, X.-P. & Hong, X. Y. SKA data take centre stage in China. Nat. Astron. 3, 1030–1032 (2019).

30. Greisen, E. W. In Information Handling in Astronomy—Historical Views (ed Heck, A.) 109–125 (Springer, 2003).
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T.A. and P.M. wrote the initial manuscript. T.A. and Y.Z. led the VLBA observations. S.F. and J.Y. contributed to the design and implementation of the observations. K.E.G., Z.P., L.I.G., K.P. and Z.Z. contributed to data analysis. All co-authors read and contributed to the manuscript and supplementary information.

Competing interests
The authors declare no competing interests.

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