Symbiosis of radio-emitting winds and a jet in a super-Eddington active galactic nucleus

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Article
**Symbiosis of radio-emitting winds and a jet in a super-Eddington active galactic nucleus**

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Super-critical accretion is the most powerful episode in nursing the black hole growth\(^1\) and works in several types of objects\(^2\)–\(^12\). Given that the inverse correlation between radio loudness and Eddington ratio\(^12\), the super-Eddington active galactic nuclei (AGNs) hold the extremely radio-quiet end of AGNs. Regarding the existence of jet in super-Eddington or radio-quiet AGNs, it’s still unclear\(^13,14\). Years of studies indicate nearly all types of super-Eddington accreting systems can launch a jet\(^3,5\)–\(^11,15,16\), with one exception: no clear evidence to show jet in super-Eddington AGNs. Observations and theoretical works suggest that super-Eddington accretion can drive high-speed wind-like outflows\(^17,18\), therefore produce radio emission through synchrotron (shocked winds) and bremsstrahlung mechanisms. However, such a radio-emitting wind has not been observed in super-Eddington systems except for the Galactic micro-quasar SS 433\(^19,20\). In principle, high resolution very long baseline interferometry (VLBI) observation can directly map the inner structure of super-Eddington AGNs. Here, we report the discovery of the coupling of jet and radio-emitting winds in a nearby super-Eddington AGN, I Zw 1. Its parsec-scale jet exhibits a wiggling, we interpret this as a jet precession. All the features make I Zw 1 act as a scaled-up version of SS 433. The observations favour that jet can be launched in extremely radio-quiet AGNs and ubiquitous in super-Eddington accreting systems. The jet wiggling or precession can produce a large aperture-angle shock, which emphasises the jet’s contribution to gas feedback. As the jet precession was also discovered in other super-Eddington systems such as SS 433\(^3\) and V404 Cygni\(^5\), it is possible that there is a correlation with each other.

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IZw 1 is one of the closest quasars at a redshift of $z = 0.0589$ \cite{21}, and is regarded as an archetypal narrow-line Seyfert 1 galaxy (NLS1) based on its optical properties \cite{22,23}. The black hole mass of I Zw 1 was estimated by the reverberation mapping method to be $M_{\text{BH}} = 9.3 \times 10^6 M_\odot$ \cite{24}. The inferred bolometric luminosity of $L_{\text{bol}} = 10^{45.50} - 10^{45.68}$ erg s$^{-1}$ (refs. \cite{25}) exceeds its Eddington limit, indicating a super-Eddington accretion system with an Eddington ratio of $\lambda_{\text{Edd}} = 2.77 - 4.20$ \cite{1}. I Zw 1 is a radio-quiet active galactic nucleus (AGN) with radio loudness $R = 0.35$ \cite{12, fn.2}. Radio emission from radio-quiet AGNs is complex and remains a subject of debate \cite{13}. On the other hand, the presence of jets in super-Eddington accretion systems, based on the inverse correlation between radio loudness and Eddington ratio \cite{12} is also a question to be explored. I Zw 1, as an extreme example of a nearby super-critical accretion and radio-quiet AGN, provides an ideal laboratory for studying the radio emission structure and its nuclear environment with high spatial resolutions.

We observed I Zw 1 on 2018 September 23 with 10 telescopes of the Very Long Baseline Array (VLBA) at L-band (1.5 GHz) and on 2020 November 17 with 19 telescopes of the European VLBI Network (EVN) plus the enhanced Multi-Element Remote-Linked Interferometer Network (e-MERLIN) at C-band (5 GHz), obtaining angular resolutions of 5 and 1 mas at L-band and C-band, respectively. In addition, we also analysed the archived Very Large Array (VLA) and e-MERLIN data. The observations and data processing are referred to Methods. The upper panel of Figure 1 shows the L-band VLBA image, displaying a continuous emission structure elongated along the east-west direction with an extent of $\sim 45$ parsec (pc). The central component is the brightest and two weaker components located on opposite sides, reminiscent of a core and two-sided jet structure. The lower panel of Figure 1 shows a higher-resolution ($\sim 1$ mas, or $\sim 1.14$ pc) image obtained from the C-band EVN plus e-MERLIN observations. The bright central component is resolved into a series of knots, all of which have brightness temperatures higher than $10^8$ K at both 1.5 and 5 GHz (Table 1) and show steep spectra (Figure 2), ruling out models involving dense star-forming regions \cite{26} and thermal free-free radiation from the hot molecular disk surrounding the nucleus \cite{27}. Furthermore, with the core identified in radio and optical (see below), the asymmetric radio structure suggests Doppler boosting effect for the approaching jet.

The nucleus of I Zw 1 has an optical position (i.e. optical nucleus: R.A. = 00$^h$53$^m$34$^s$.933288$^\pm$0.000187, DEC. = +12$^\circ$41$'$35$''$.93081 $\pm$ 0.00017, J2000) \cite{28,29}, closer to the component W a (Figure 1), which has the highest brightness temperature $\log T_B = 12.39$ K. An AGN core generally has a flat radio spectrum due to the optically-thick synchrotron emission ($\alpha > -0.5$ \cite{3}). In the full resolution image of C-band, the component W a fits well with the optical nucleus position and has a flat radio spectrum (Figure 2, $\alpha \sim -0.4$). Therefore, component W a is most likely to be the radio core. As we produced the ridgeline and radio spectral index map based on the full resolution L-band and tapered C-band images, only component W can be identified in the relatively low-resolution images. Therefore, in the discussion of jet structures, we alternatively selected the

\[ \lambda_{\text{Edd}} = \frac{L_{\text{bol}}}{L_{\text{Edd}}} \]

$L_{\text{bol}}$ is the bolometric luminosity, $L_{\text{Edd}} = 3.2 \times 10^4 (M_{\text{BH}}/M_\odot) L_\odot$ is the Eddington luminosity, $M_{\text{BH}}$ is the black hole mass.

\[ R = 1.3 \times 10^5 (L_5/L_B) \]

$L_5$ is the radio luminosity at 5 GHz and $L_B$ is the optical luminosity of the nucleus at $\lambda_B = 4400$ Å; Radio-quiet AGNs are defined as $R < 10$.\n
\[ S_\nu \propto \nu^\alpha ; \]

$S_\nu$ is the flux density and $\nu$ is the frequency.
flattest radio spectral position (see Figure 2) along the ridgeline as the central reference point for the jet trajectory, which is consistent with component W within 1-σ uncertainty. The location is at ∆R.A. = 2.18 (mas, J2000), ∆DEC. = −2.18 (mas, J2000) with respect to the Gaia optical nucleus. Regarding the jet reference, the radio spectral index decreases rapidly in both extending directions (right panel of Figure 2), further confirming the core environment and the jet originated from there. The steepening of the spectra with increasing distance is due to the radiative losses of synchrotron-emitting plasma.

There is no theoretical consensus on whether there are jets in a super-Eddington system and how the jets are produced. The observed inverse correlation between the radio loudness and the Eddington ratio suggests that the jet is progressively suppressed as the Eddington ratio increases, mainly due to the Papaloizou-Pringle instability. As the accretion rate approaches about one-third of the Eddington limit, the Papaloizou-Pringle instability destroys the jet-producing region of the disc, suppressing the jet production. Relativistic winds arising from super-Eddington accretion disc are sometimes considered to be a secondary mechanism for further jet suppression. However, recent studies have shown that a relatively rapidly developing magnetic field may induce magneto-rotational instability that can stabilise the disc, thus giving a chance to form the jet. There is growing observational evidence for the existence of jets in super-critical accretion systems, such as accreting X-ray pulsars, black hole X-ray binaries, and tidal disruption events.

In the 1.5 and 5 GHz images, we find an excess of transverse emission in the north-south direction (denoted as N and S at 1.5 and 5 GHz). The transverse emission at 5 GHz is further confirmed in the tapered image and well overlapped with the 1.5 GHz image (contours in the left panel of Figure 2). We find the transverse emission seems to arise from the bright jet components (W/Wa and E2), and their high brightness temperatures make them unlikely to result from star-forming activities. These features resemble the radio structure in SS 433, in which the transverse emission has a steep radio spectrum α = −1, indicating that it originates from wind-like outflow (shocked winds) through the synchrotron process. The wind-like equatorial outflow in SS 433 maintains at a projected distance of ∼ 20 mas from the core, corresponding to a size of ∼ 10^{8.5} R_g, where R_g is the Schwarzschild radius. By comparison, the transverse emission in I Zw 1 also has a steep radio spectrum (α ∼ −1, Figure 2) and the base of the transverse emission maintains at a size of ∼ 10 mas, corresponding to ∼ 10^{7.0} R_g, which can be explained by a similar synchrotron process of the relativistic electrons accelerated by the wind-driven shocks.

The wind-like outflow in the super-Eddington regime has long been suggested by analytical and numerical models. It is found that the wind-like outflow is ubiquitous in black hole X-ray binaries when it is in a high accretion state close to the Eddington limit. There are also signs of wind-like radio-emitting outflows in high accreting AGNs. I Zw 1 do host strong multiscale outflows: an ultrafast wind-like outflow with a velocity of > 0.25 c obtained from the fitting of the iron K-line profile, an ionised ultraviolet gas outflow with a velocity of 1870 km s^{-1} and a neutral gas outflow with a velocity of 45 km s^{-1}. Interestingly, the neutral gas outflow coincides with the direction of N and S components.

The radio emission from the wind-like outflow (shocked winds) in I Zw 1 may arise from the
jet collision with the massive outflow (perpendicular to an outer accretion disk) as was suggested in SS 433 or a parsec-scale dense molecular gas disc/torus (jet-induced wind-like outflow, when jet-ISM collision, the jet plasma tends to flow laterally along the decreasing gradient), or both. The jet-ISM collision interpretation is supported by the parameter $\eta < 1$ (Figure 6), which suggests that a dense environment hinders the expansion of the jet plasma. Further support is provided by recent observations of I Zw 1 at other bands: the direction of the kilo-parsec-scale molecular gas disc was found to be approximately along the parsec-scale jet direction here, and a radius of $\sim 7$ mas ($\sim 8$ pc) torus is also proposed.

Furthermore, we know that jet direction is a good indicator of BH spin or inner accretion disk orientation, i.e. jet is either along the BH spin direction or inner accretion disk axis. Our observations reveal that the jet direction in I Zw 1 is along the kpc-scale molecular disk, which is suggesting that the kpc-scale molecular disk (direction of the axis) is tilted with the inner accretion disk axis or BH spin.

Methods

VLBI observations We observed I Zw 1 on 2018 September 23 with ten antennas (full array) of the Very Long Baseline Array (VLBA) and on 2020 November 17 with nineteen antennas of the European VLBI Network (EVN) plus the enhanced Multi-Element Remote-Linked Interferometer Network (e-MERLIN). The VLBA observations were carried out at L-band (1.5 GHz, the project code BY145), and the EVN+e-MERLIN observations were conducted at C-band (5 GHz, the project code EY037), respectively. The total VLBA observing time is 2 h with a data recording rate of 2 Gbps, while the total time of the EVN+e-MERLIN observation is 8 h with a data recording rate of 4 Gbps. Both observations were performed in the phase-referencing mode, using J0056+1341 (R.A.: 00°56′14.8161″, Dec.: +13°41′15.755″) as the phase reference calibrator.

VLBI data reduction We calibrated the VLBI data in the Astronomical Image Processing System (AIPS), a software package developed by the National Radio Astronomy Observatory (NRAO) of U.S., following the standard procedure. A-prior amplitude calibration was performed using the system temperatures and the antenna gain curves provided by each station. The earth orientation parameters were obtained and corrected using the measurements from the U.S. Naval Observatory database and the ionospheric dispersive delays were corrected based on a map of the total electron content provided by the GPS satellite observations. The opacity and parallactic angles were also corrected based on the auxiliary files attached to the data. The delay of the visibility phase and the telescope bandpass were calibrated using the bright radio source 3C 454.3. Finally, we performed a global fringe-fitting on the phase-referencing calibrator J0056+1341 by assuming a point source model to solve miscellaneous phase delays.

The phase calibrator J0056+1341 shows a core and a jet extending $\sim 100$ mas to the north (see the 1.5 and 5 GHz images in Figure 5). We first performed self-calibration to the calibrator and obtained its CLEAN model, which was then used as the input model to re-solve the phases in AIPS. This operation can eliminate the phase reference errors due to the jet structure. We applied
the solutions obtained from the calibrator by re-running fringe fitting to the target. Next, the data from the target source is exported to DIFMAP for deconvolution. No self-calibration was used for the target since it is too weak and resolved, with a signal-to-noise ratio of \( \sim 30 \) and \( \sim 14 \) at 1.5 and 5 GHz, respectively.

We performed CLEAN and model fitting algorithms to produce radio maps. The CLEAN algorithm is suitable for compact and isolated emission structures, however, it has serious problems in recovering a complex emission source when the uv sampling is poor, as is always common in VLBI observations. In contrast, the model fitting procedure has the desirable property to take into account the statistical details, and is suitable for reliable parametric representation of the sparsely sampled visibility data. It is important to note that the solutions for model fitting are more or less not unique when complex structures are to be handled. Here we use the delta function rather than the usually used Gaussian function for model fitting, as the delta function has fewer parameters than the Gaussian model and is sensitive to asymmetric emission regions. The resulting images are shown in Figures 3 and 4. The CLEAN and model-fit images at both L- and C-band are very consistent, although several components (X, E3a, and E3b) in the C-band image with delta-function model fitting have a slightly different structure to that in the CLEAN image. The difference is mainly in the weak and diffused structures due to the reason mentioned above, i.e., the poor uv-coverage particularly on the long baselines and the limited common observing time on the east-west baselines. I Zw 1 also shows residual emission in the north and south directions at both 1.5 and 5 GHz, after removing the central bright components, strongly indicating that some diffused emission cannot be recovered at the full resolution map. Therefore, we also produced a uv-tapered map to reduce the weight of the long-baseline visibilities (and thus also reduce the resolution) in an attempt to recover the weak and extended emission.

Archived MERLIN data Two MERLIN C-band (4.99 GHz) datasets of the target I Zw 1 are available in the MERLIN data archive. These data were observed on 1996 December 1 with six antennas: Defford (De), Cambridge (Ca), Knockin (Kn), Darnhall (Da), Mark II (Mk), and Tabley (Ta), and 1997 November 6 with five antennas (De, Ca, Kn, Da, Ta). The two MERLIN observations provide a minimum baseline of 0.07 M\( \lambda \) (\( \sim 4 \) km) and 0.47 M\( \lambda \) (\( \sim 28 \) km), respectively, and a maximum baseline of 3.62 M\( \lambda \) (\( \sim 217 \) km) for both with a resolution of \( \sim 0.1 \) arcsec. The calibrator J0106+1300 (RA: 01h06m33.3558s, Dec: +13°00′02.608″) was used for phase reference, and 3C 286 and OQ 208 were used as the primary flux density scale and bandpass calibrator for both datasets. The phase of the archived MERLIN data has already been calibrated in AIPS, including preliminary bandpass and flux density scale calibration, phase and amplitude calibrations. We imported the calibrated data into DIFMAP for manual imaging and self-calibration. In both datasets, the target is detected with a signal-to-noise ratio above 7, self-calibration has not been used. A two-dimensional Gaussian model was fitted to the visibility data to obtain the integrated and peak flux density, which are shown in Table 2.

Archived VLA data We retrieved the raw visibility data of I Zw 1 observed by the Very Large Array (VLA) from the NRAO data archive, including historical VLA and the newly observed Karl 5

5 http://www.merlin.ac.uk/archive/
6 https://archive.nrao.edu/archive/advquery.jsp
G. Jansky VLA (JVLA) data. Although some data have been published (see Table 2), to ensure consistency in the data reduction, we performed a manual calibration for all available datasets using the Common Astronomy Software Application (CASA v5.1.1)\textsuperscript{53}. Our data reduction followed the standard routines described in the CASA cookbook. We adopted the ‘Perley-Butler 2017’ flux density standard\textsuperscript{54} to set the overall flux density scale for the primary flux calibrator, and then bootstrapped the secondary flux density calibrators and the target. For the historical VLA datasets, we determined the gain solutions using a nearby phase calibrator and transferred them to the target I Zw 1. For the JVLA datasets, we also determined antenna delay and bandpass by fringe-fitting the visibilities. For the data observed after 1998, we performed an ionosphere correction using the data obtained from the CDDIS archive. Deconvolution, self-calibration, and model-fitting were performed in DIFMAP. The final images were created using natural weighting. Due to the good uv-coverage of the VLA, simple emission structure, and high signal-to-noise ratio (SNR > 9), the VLA data allow for self-calibration using a well-established model. For data with lower SNR, we used three times the image noise as the upper limit for the flux density.

**Astrometry of the VLBI data** The position uncertainty of the CLEAN components was estimated as $\sim 20\%$ of the restoring beam dimensions in the naturally-weighted image. For isolated components, we estimate the uncertainties as $\text{FWHM}/(2 \times \text{SNR})$, where FWHM is the full width at half maximum of Gaussian components or the restoring beam for Delta components, and SNR is the ratio of emission peak to the noise. The position errors of the phase-referencing calibrator are $0.34 \, \mu\text{as}$ and $0.07 \, \mu\text{as}$ in 1.5 and 5 GHz images, respectively.

In phase-referencing observations, the coordinates of the target are referenced to the close calibrator, however, during the self-calibration process, the absolute coordinate position of the phase-referencing calibrator is lost and the brightest feature of the image is shifted to the phase centre of the map. In general, due to the frequency-dependent shift of the optically thick component’s peak and the slightly different distribution of the radio emission at different resolutions, the brightest component may not be at the same position from one observation to another. This would induce an offset between two images, in the form of astrometric error. The alignment between the images of the two observations can be done using an optically thin component, whose position is less affected by the frequency-dependent opacity effect, as a reference.

For VLBI observations in both L and C bands, we used J0056+1341 as the phase-referencing calibrator, which has a flat-spectrum radio core. The absolute astrometric position of J0056+1341 is derived from the VLBA X-band (7.6 GHz) observations. Since neither the C- and X-band data from Astrogeo\textsuperscript{7} are self-calibrated, the core-shift at C-band can be directly estimated as $\Delta\text{R.A.}$ $\sim 0.70 \, \text{mas}$, $\Delta\text{DEC.} \sim -0.20 \, \text{mas}$ with respect to the 7.6 GHz data, the most accurate absolute astrometric position of J0056+1341 at C-band can be determined accordingly. J0056+1341 also has a significant offset between C and L bands (see Figure 5) in our observations, and the offset of the VLBA L-band image is determined using the optically thin component of the jet, estimated as $\Delta\text{R.A.} = 1.742 \pm 0.035 \, \text{mas}$, $\Delta\text{DEC.} = -3.228 \pm 0.035 \, \text{mas}$ to the EVN+e-MERLIN C-band image.

\textsuperscript{7}http://astrogeo.org/
For target I Zw 1, we use the position of the brightest component (optically thin) in the tapered EVN+e-MERLIN C-band image (the upper panel in Figure 4) to match the VLBA L-band image which has a similar beam size. The peak position of the L-band image was moved to match the C-band image by \( \Delta \text{R.A.} = 1.3308 \pm 0.035 \text{mas}, \Delta \text{DEC.} = -0.77024 \pm 0.035 \text{mas} \). The optical emission centroid of the second data release of the Gaia mission is R.A. = 00h53m34.933288 ± 0.00012, DEC. = +12°41′35″.93081 ± 0.00017 (J2000), including astrometric excess noise error of 0.14 mas. The optical core I Zw 1 located in the radio emission region.

The Gaia position indicates the compact and brightest feature in the optical band, which we use as the optical nucleus. In radio bands, we identify the radio core based on the compact component with a flat spectrum, furthermore, an AGN core is defined as the origin of a jet which should naturally locate on the jet trajectory. In the L-band image, the component W is closer to the optical nucleus and has the flat radio spectrum, the radio brightness temperature is \( \log T_B = 10.57 \text{ K} \). In the C-band image, the component Wa has the highest brightness temperature (\( \log T_B = 12.39 \text{ K} \)) and is closest to the optical nucleus, which is most possible as the radio core. However, the component Wa is slightly offset from the jet trajectory (Figure 7), which makes it complex to be used as the reference point for the jet trajectory. As we produce ridgeline and radio spectral index map (Figure 2) based on the tapered (with reduced resolution) C-band and L-band images, only the component W can be identified there. On the discussion of jet structures, we have alternatively selected a reference point that located at the jet ridgeline and shows the flattest radio spectrum (the curve peak in the right panel of Figure 2), with no surprise that the position is consistent with the component W within 1-\( \sigma \) position errors (see Figure 7).

**Radio Spectrum** To obtain the radio spectral index, we first checked the variability of I Zw 1. Figure 9 shows the radio flux density versus the observing epoch, and the largest variability we can identify is \( \sim 8\% \), which is from the VLA A-array observations at C-band between the epoch 1983 and 1995. Since there is no significant variability on a time scale of \( \sim 30 \) years, we plot the radio flux density versus the frequency in Figure 10. The least-square fitting gives an overall radio spectral index of \( -0.88 \pm 0.10 \). From Figure 10, we found the radio flux density changes with the size of the synthesis beam. The radio spectral index between 1.4 and 5 GHz by using the datasets with a similar resolution, i.e., 1.3 \( \sim \) 1.5 and 4.3 \( \sim \) 5.3 arcsec, is \( -0.69 \pm 0.13 \) and \( -0.60 \pm 0.03 \), slightly flatter than the overall value.

For the high-resolution data observed with the VLBA and EVN+e-MERLIN, in order to obtain its spectral index distribution, we obtained a spectral index map following the procedure described in 30. Here we used the uv-tapered image by 0.5 at 20 \( \lambda \) at 5 GHz and restored it to match the 1.5 GHz map. The spectral index was calculated pixel by pixel between the 1.5 and 5 GHz total intensity maps. For a given frequency, pixels with an intensity less than 3\( \sigma_{\text{rms}} \) were removed. The spectral index map between 1.5 and 5 GHz is shown in the left panel of Figure 2.

**Radio flux density and Brightness Temperature** We estimated the uncertainties of integrated flux density \( S_i \) and peak flux density \( S_p \) using the expression \( \sigma_i = \sqrt{2.5\sigma^2_{\text{rms}} + (0.01S_i)^2} \) and \( \sigma_p = \sqrt{\sigma^2_{\text{rms}} + (1.5\sigma_{\text{rms}})^2} \approx 1.8\sigma_{\text{rms}} \), respectively, where \( \sigma_{\text{rms}} \) is the RMS noise estimated in

\[ \text{https://gea.esac.esa.int/archive/} \]
a blank sky zone far away from the target source. The radio brightness temperature was estimated by using the formula \(^57\):

\[
T_B = 1.8 \times 10^9 (1 + z) \frac{S_i}{\nu^2 \phi_{\text{min}} \phi_{\text{maj}}} \text{ (K)},
\]

where \(S_i\) is the integrated flux density of each Gaussian model component in units of mJy (column 5 of Table 1); \(\phi_{\text{min}}\) and \(\phi_{\text{maj}}\) are the minor and major axes lengths of the full width at half maximum (FWHM) of the Gaussian model or the restored beam in milli-arcsec; \(\nu\) is the observing frequency in GHz (column 2 of Table 1), and \(z\) is the redshift. To estimate the component size, we fit a Gaussian model to the 1.5 and 5 GHz data by using natural weights, the fitting only fills several well symmetric and isolated components (see column 6 of Table 1). Note that the Gaussian model is not a good representation of the emission distribution when the complex radio structure is encountered in a poor uv-coverage, for those components without a Gaussian model representation, we use the synthesised beam instead as the component size. The estimated 1.5 GHz and 5 GHz radio brightness temperatures are listed in Column 7 of Table 1. Since the measured component size is only the upper limit, the radio brightness temperature should be considered as the lower limit.

We also estimated a total radio flux density using the tapered images at 1.5 and 5 GHz, which is 2.636±0.098 and 0.614±0.047 mJy, respectively, the corresponding angular size is \(\sim 50\) and \(\sim 40\) mas, respectively.

**Model-fitting of the helical jet structures** To obtain the trajectory of the main jet structures, we cleaned the C-band data by using a natural weight and a Gaussian tapering of 0.5 at uv radius 10 M\(\lambda\), the clean procedures stopped when the peak flux density in the dirty map dropped below \(7\sigma = 5.75 \times 10^{-5}\) Jy/beam. The clean components appropriately show the linear jet trajectory, and here we designated the spectral peak along the jet line as the emitting origin and the reference, which is located at R.A. = 2.18 (mas), DEC. = −2.18 (mas) with respect to the Gaia position.

The total synchrotron emission from a single optically thin jet knot where the synchrotron-emitting plasma undergoes adiabatic expansion can be scaled \(^45\) as

\[
J(\nu) \propto \nu^{1-p/2} R^{1-3p/2},
\]

where \(p = 1 - \alpha\) and \(\alpha\) is the spectral index of the emission \((S_\nu \propto \nu^\alpha, \nu\) is the frequency, \(R\) is the radius of a jet knot, assuming symmetric expansion of the approaching and receding jets. By taking the expansion of the plasma to be the form

\[
R \propto t^\eta = (\frac{D r}{\nu_i})^\eta,
\]

where \(r\) is the angular distance to the core and \(\nu_i\) is velocity on the sky plane, \(D\) is the distance from the observer to the target, \(\eta\) indicates the linearity of jet expansion \((R \propto t^\eta)\), for linear expansion \(\eta = 1\) and for the deceleration of the expanding plasma, \(\eta < 1\). We can get

\[
J(\nu) \propto \nu^{1-p/2} \nu_i^{-3p/2} r^{\eta-3p/2} \eta^{1-3p/2},
\]
Then the ratio of radio flux densities as seen by the observer is

\[ \frac{S_{\text{app}}}{S_{\text{rec}}} = \left( \frac{1 + \beta \cos i}{1 - \beta \cos i} \right)^{k+\alpha} \left( \frac{L_{\text{app}}(t_{\text{app}})}{L_{\text{rec}}(t_{\text{rec}})} \right), \tag{5} \]

where \( S_{\text{app}} \) and \( S_{\text{rec}} \) are the flux density for approaching and receding jet components, respectively, \( \beta = \frac{v}{c} \) is the jet speed in unit of speed of light \( c \). \( t_{\text{app}} \) and \( t_{\text{rec}} \) are the times at which light leaves the approaching and receding knots, respectively, and \( L_{\text{app}} \) and \( L_{\text{rec}} \) is their luminosities, \( k \) takes value 2 in our case for a continuous jet. Here we know the velocities on the sky plane (or proper motions) at approaching \( v_{\text{app}} \) and receding \( v_{\text{rec}} \) jet knots have the relation

\[ \frac{v_{\text{app}}}{v_{\text{rec}}} = \frac{1 + \beta \cos i}{1 - \beta \cos i}, \tag{6} \]

then

\[ \frac{S_{\text{app}}}{S_{\text{rec}}} = \left( \frac{r(t_{\text{app}})}{r(t_{\text{rec}})} \right)^{\eta - \frac{3\beta}{2}} \left( \frac{1 + \beta \cos i}{1 - \beta \cos i} \right)^{-\frac{1-3\beta}{2} + \frac{\psi + 1}{2}}, \tag{7} \]

where \( S_{\text{app}} \) and \( S_{\text{rec}} \) are the flux densities of a corresponding pair of approaching and receding knots, \( r(t_{\text{app}}) \) and \( r(t_{\text{rec}}) \) are their proper motion distances to the core. Here we fit our data with the model above, \( \eta \) as a free parameter, and introduce a new free parameter \( f_0 \) as the flux density scale, i.e.

\[ f_0 = \frac{f_{0,\text{app}}}{f_{0,\text{rec}}} = \frac{1 + \beta \cos i}{1 - \beta \cos i}, \tag{8} \]

where \( f_{0,\text{app}} \) and \( f_{0,\text{rec}} \) are the flux density at the same distance in approaching and receding jet, respectively. At the same jet direction we have

\[ S \propto r^{\eta - \frac{3\beta}{2} + \frac{\psi + 1}{2}} f_0^{1 + \beta \cos i}, \tag{9} \]

The flux density scale \( f_0 \) of approaching and receding jet and the jet expansion parameter \( \eta \) can be constrained based on the variation of the jet flux density with the distance from the core. In Figure 6, we show the constraints on parameters, and we take one percent of the integrated flux density as the error. Due to the limited data points and the effect of jet helical motion and colliding with dense medium, for example, the radio flux density at radius \( \sim 1 \) and \( \sim 10 \) mas (which does not take to constrain the parameters). In order to give a reasonable estimate of parameter \( f_0 \) and \( \eta \), we select bright components for fitting, which are marked with blue (approaching jet) and red (receding jet) in Figure 6), we firstly fit the data points at the approaching jet with least-square, which yield \( f_{0,\text{app}} = 3.10 \pm 0.07 \) and \( \eta = 0.22 \pm 0.02 \), then fit the data points at receding jet with \( \eta \) fixed at 0.22, i.e. assuming the same environment for both approaching and receding jets, which yields the parameter \( f_{0,\text{rec}} = 2.80 \pm 0.05 \), with the formula 8, we can get the parameter \( \beta \cos i = 0.050 \pm 0.002 \).

We used a relativistic jet precession model \(^{58}\), where the jet projected on the plane of the sky can be determined by the following parameters: jet velocity \( \beta = \frac{v}{c} \) where \( v \) is the jet speed; \( i \) is the jet inclination angle to the line of sight; the opening angle of the precessing jet cone \( \psi \);
the jet position angle to the north on the plane of the sky anti-clockwisely $\chi$; angular velocity of jet precession $\Omega$ ($\Omega = 2\pi/P$, where $P$ is precession period); initial angle of jet precession or the precession angle of terminal jet components to the line of sight $\theta$, positive value for an anti-clockwise rotating and vice verse. In this model, $\beta$ and $\Omega$ are tightly correlated with $i$ and only the $i$ can be fitted separately, so we taking the relation $\beta \cos \theta = 0.050 \pm 0.002$ for an overall helical jet model-fitting. The parameters were determined by performing a Markov Chain Monte Carlo (MCMC) algorithm implemented with the ‘emcee’ package, the off-axis features of the jet have been removed from the fitting and we only use the approaching jet (eastern part) for the model-fitting.

The posterior probability of the MCMC approach is shown in Figure 8, where each parameter is well determined. The best-fit values are those with the maximum posterior probability (50\% quantiles of marginalised posteriors). Not surprisingly, the parameter $i$ and $\Omega$ are tightly correlated, however with the good probability distribution of the parameter $i$, both parameters $i$ and $\Omega$ are well determined simultaneously. The fit yields $i = 1.52^{+0.01}_{-0.02}$ (rad), $\psi = 0.10^{+0.02}_{-0.02}$ (rad), $\chi = 1.77^{+0.01}_{-0.01}$ (rad), $\theta = -2.38^{+1.06}_{-1.06}$ (rad) and $\Omega = 0.15^{+0.09}_{-0.06}$ (rad/yr) corresponding to $P = 41^{+27}_{-15}$ (yr). With the relation $\beta \cos i = 0.050 \pm 0.002$ and the estimated parameter $i$, the jet velocity can be determined as $v = 0.70 - 1$ (c).

In Figure 7, we show the jet trajectory presented by the parameters above.


**Acknowledgements** This work is supported by the National Science Foundation of China (11721303, 11991052), the National Key R&D Programme of China (2016YFA0400702, 2018YFA0404602, 2018YFA0404603), and Shanghai Sailing Program (21YF1455300). SY is supported by an Alexander von Humboldt Foundation Fellowship. MFG is supported by the National Science Foundation of China (grant 11873073). The European VLBI Network (EVN) is a joint facility of independent European, African, Asian, and North American radio astronomy institutes. e-MERLIN is a National Facility operated by the University of Manchester at Jodrell Bank Observatory on behalf of STFC. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work has made use of data from the European Space Agency (ESA) mission *Gaia* (https://www.cosmos.esa.int/gaia), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement. Scientific results from data presented in this publication are derived from the EVN project EY037 and the VLBA project BY145. The VLBI data processing and MCMC simulation in this work made use of the compute resource of the China SKA Regional Centre prototype, funded by the Ministry of Science and Technology of China and the Chinese Academy of Sciences.

**Author Contribution** X.-L.Y. designed the VLBI observations, made the VLBI data reduction and model-fitting, interpreted the results, and drafted the manuscript. J.Y. double-checked the results by manual data reduction. S.Y. and X.-L.Y. contribute to writing the VLBA observing proposal, A.-L.W., X.-L.Y., and T.A. contribute to writing the EVN plus e-MERLIN observing proposal. All the authors discussed the results and commented on the manuscript.

**Competing Interests** The authors declare that they have no competing financial interests.

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Table 1: **Model-fitting results of the radio components detected in I Zw 1 with the VLBA L-band and EVN+e-MERLIN C-band observations.** Column 1: component name; Column 2: frequency; Column 3: right ascension offset, the uncertainty is 0.47 and 0.12 mas for 1.548 and 4.926 GHz, respectively; Column 4: declination offset, the uncertainty is 1.14 and 0.31 mas for 1.548 and 4.926 GHz, respectively; Column 5: integrated flux density; Column 6: angular size of components (if given) from a Gaussian model-fit; Column 7: lower limit of the radio brightness temperature.

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<th>DEC.Off (mas, J2000)</th>
<th>$S_i$ ((\mu)Jy)</th>
<th>Size (mas)</th>
<th>Log $T_b$ (K)</th>
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Figure 1: **VLBI images of the I Zw 1 in 1.54 and 4.92 GHz.** The upper panel shows the cleaned L-band image and the lower panel shows the cleaned C-band image. In the L-band image, the beam size is $11.5 \times 4.67$ mas and the rms noise is 0.025 mJy/beam. In the C-band image, the beam size is $3.22 \times 1.14$ mas and the rms noise is 0.007 mJy/beam. At both images, the red asterisks indicate the Gaia position, the uncertainty of the Gaia position is $\Delta \alpha = 0.18$ and $\Delta \phi = 0.17$ mas at R.A. and DEC., respectively, including an astrometric excess noise error of 0.14 mas. All the images are produced with a natural weighting and the map reference is at the Gaia position, the contours are at $3\sigma \times (-1, 1, 1.41, 2, 2.83, ...)$. At the redshift of I Zw 1, 1 mas corresponding to 1.139 pc. The components are recognised based on the delta-model-fitted images except for the component X, which we cannot match with the model-fitted image.
Figure 2: **1.5–5 GHz spectral index distribution of I Zw 1 on the parsec scale.** Left panel: the image was produced by using the naturally weighted clean map at 1.54 and 4.92 GHz. The region with radio flux density below $3\sigma$ was set as blank (white), i.e. the outer region of the red and white lines, respectively. Radio spectral indexes within both red and black lines are most reliable. The cyan asterisks indicate the jet ridgeline obtained from the tapered 4.92 GHz image; Right panel: the spectral index distribution along the ridgeline, the positive radius corresponding to the positive right ascension coordinates, and vice versa, and the *Gaia* position is set as the reference. The blue belt is the uncertainty of spectral index, in both panels the red asterisk indicates the *Gaia* position.
1 Supplementary

The jet wiggling The jets at both 1.5 and 5 GHz is strongly nonlinear, with a position angle coverage of 18° at the approaching jet (the east branches). The non-linearity grows with the distance from the core and the jet wiggling is more likely periodic than random (Figure 7), hints a helical jet structure. We use the components from δ-model fitting of the tapered 5 GHz image to depict the ridgeline of the jet limb (see Methods), and the ridgeline clearly shows a helical pattern. In the 5 GHz image (Figure 4), we also found the counter jet, which is more clear in the tapered image (Figure 4), indicating the two-sided jet. Under the assumption of symmetrically approaching and receding jets, we can estimate the inclination angle $i$ to the line of sight and the jet velocity $\beta$ ($\beta = v/c$, where $v$ is velocity, $c$ is the speed of light, see Methods). Figure 6 shows the radio flux density versus distance from the core. The radio emission at $\sim 1$ and $\sim 10$ mas region may be due to additional Doppler boosting of the helical jet and/or collisions with the surrounding medium, therefore which was not used for fitting. Based on the data, we give $\beta\cos i \sim 0.050 \pm 0.002$. This model suggests a deceleration of the expanding jet plasma (expansion factor $\eta = 0.22 \pm 0.02$, $\eta = 1$ for a linear expansion, see more details in Methods), consistent with a dense environment.

Employing the equation between the jet velocity and the inclination angle, we can fit the geometric parameters of the helical jet structure. The helical model allows a good representation of the jet structure, and in the MCMC fitting we can determine the parameters such as the jet inclination angle to the line of sight $i = 87.6^{+0.5}_{-1.1}$ (deg), opening angle of helical jet cone $\psi = 5.7^{+1.1}_{-1.1}$ (deg), jet position angle with respect to the north on the sky plane anti-clockwisely $\chi = 101.4^{+0.5}_{-0.5}$ (deg), rotation period of jet position angle $P = 41^{+27}_{-15}$ (year) and jet velocity $v = 0.70 - 1.0$ (c). Note that the jet velocity is estimated by using the estimated value of inclination angle $i$ and the relation $\beta\cos i \sim 0.050 \pm 0.002$, the jet velocity is higher than the ultra-fast wind speed ($0.26c$) in 1 Zw 1.

The helical jet structure in the super-Eddington accreting system 1Zw 1 enhances the similarity between super-Eddington X-ray binaries such as SS 433 and V404 Cygni, and with three sources so far showing helical jets at super-Eddington accretions, we are almost coming to a consensus and a strong demand for a unified model. The most plausible mechanism in driving the helical jet structures is accretion disk precession. If the axis of the accretion disc is tilted to the black hole spin, the frame-dragging generated by the black hole rotating can lead to particle precessing inside the disc, a.k.a. the Lense-Thirring effect. The frame-dragging effect decreases with distance and becomes negligible at large distances. Therefore an inclined viscous accretion disk with respect to the spin of the black hole will produce warps in the disk which force the alignment between the axis of the innermost accretion disk and spin of the black hole, this phenomenon is known as the Bardeen-Petterson effect. Our observations of 1Zw 1 demonstrate kpc-scale molecular disk (direction of the axis) is tilted with the inner accretion disk axis or BH spin (see main text), both hint the Lense-Thirring effect is at work.

The preset disk tilt/warping can be driven by several mechanisms, for example, the tides from a companion star or a black hole, winds, magnetically driven outflows and radiation driven warping instability, a.k.a. the Pringle’s instabilities. Interestingly, a high or super-Eddington accretion is often coupled with the wind and the Pringle’s instabilities, supporting the helical
jet in super-Eddington accreting systems. The period of Lense–Thirring precession $P \propto M/a^*_{\ast}$ satisfies the scaling relation of black hole mass $M$, where $a^*_{\ast}$ is the dimensionless black hole spin. By comparison, we have calculated the value $P a^*_{\ast}/M$, where $P$ is in $\text{min}$ and $M$ is in $M_\odot$, which is $\sim 0.07 - 0.09$ and $\sim 1.35 a^*_{\ast} - 3.84 a^*_{\ast}$ for V404 Cygni and I Zw 1, respectively, the spin parameter of I Zw 1 is unknown. If considering the low and intermediate spin parameters ($a^*_{\ast} \sim 0.1^{67}$), the helical jet structure in I Zw 1 is consistent with the Lense–Thirring precession in V404 Cygni.

Large-scale radio emission Figure 10 shows I Zw 1 has a power-law radio spectrum over the entire observed frequency range, indicating the dominance of synchrotron radiation, which does not significantly affect by the collection areas, see Figure 11, where the intercept between the L-band and C-band lines is the spectral index. The overall spectral index is $-0.88 \pm 0.10$, there is no significant decrease at higher frequencies, indicating a continuous replenishment of fresh electrons, while the central engine remains active. Interestingly, the spectral index at the farthest edge of the jet from the core is $\sim -1.8$ (Figure 2), which are inconsistent with the overall spectral index estimated for the larger area but suggesting a non-jet origin as the spectral index decreases along the jet direction. The large-scale flux density is dominated by diffuse radio emission with only a fraction ($\sim 30\%$ out of 60 kilo-parsec scale and $\sim 47\%$ out of $\sim 1.54$ kilo-parsec scale emission in 1.5 GHz) coming from the (parsec-scale) core region. The distribution of radio flux density can be fitted as

$$S_L = (1.40 \pm 0.16) r^{0.165 \pm 0.010} \quad \text{and} \quad S_C = (0.86 \pm 0.01) r^{0.137 \pm 0.002},$$

where $S_L$ and $S_C$ is the L and C-band flux density in mJy, and $r$ is the angular size in mas (Figure 11).

Both star-forming activities and relativistic winds can produce large-scale radio emission $^{13}$, here the star-forming activities are preferentially referred to supernovae or supernova remnants due to the power-law spectrum. Assuming the whole radio emission is from the star-forming activities, we can estimate the star formation rate (SFR) with radio emission by using the SFR-radio relation (formula 3 in refs.$^{12}$). The largest SFR can be obtained with the datasets: NVSS at 1.4 GHz, AE0022 at 1.4 GHz and 4.86 GHz, AA0048 at 14.94 GHz, which is $\sim 20 M_\odot yr^{-1}$, similar with the estimate in (refs.$^{69}$, $\sim 26 M_\odot yr^{-1}$), suggesting the large scale radio emission can be fully from star-forming activities. Whereas the SFR-radio relation is quite crude that we can not fully rule out the contribution of wind-like outflow, the radio-emitting wind at a large scale (a few kiloparsec scale) is negligible. In addition, the radio-emitting wind is still possible at the intermediate scale (tens of parsec scale), as there are no compact supernovae and supernova remnants detected by VLBI and e-MERLIN observations $^{70}$. 


Table 2: Summary of historical observations and results for 1Zw 1. Column 1: telescope; Column 2: frequency; Column 3: project ID and references for datasets publication (NG: Not given; *: Original data is not available, the result is from literature); Column 4: observing date; Column 5: time-source; Column 6: observing bandwidth; Column 7 - 9: beam major axis, minor axis, and position angle; Column 10: integrated flux density; Column 11: peak flux density.

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<th>(\nu)</th>
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<th>BW</th>
<th>(\theta_{maj})</th>
<th>(\theta_{min})</th>
<th>P.A.</th>
<th>(S_i)</th>
<th>(S_p)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>(GHz)</td>
<td></td>
<td></td>
<td>(min)</td>
<td>(MHz)</td>
<td>(arcsec)</td>
<td>(arcsec)</td>
<td>(degree)</td>
<td>(mJy)</td>
<td>(mJy beam(^{-1}))</td>
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<td>46</td>
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Figure 3: **Radio images of the I Zw 1 in 1.54 GHz obtained with VLBA observation.** The left panel shows the tapered image with a beam size of $19.9 \times 14.9$ mas, the rms noise is 0.06 mJy/beam. The right panel shows the delta-model-fitted image with a beam size of $11.5 \times 4.67$ mas and the rms noise is 0.029 mJy/beam. In the delta-model-fitted image, the black crosses show the location of components, the red asterisks indicate the Gaia position, the uncertainty of the Gaia position is $\Delta \alpha = 0.18$ and $\Delta \phi = 0.17$ mas at R.A. and DEC., respectively, including an astrometric excess noise error of 0.14 mas. All the images are produced with a natural weighting and the map reference is at the Gaia position, the contours are at $3\sigma \times (-1, 1, 1.41, 2, 2.83, \ldots)$. At the redshift of I Zw 1, 1 mas corresponding to 1.139 pc.
Figure 4: Radio images of the I Zw 1 in 4.92 GHz obtained with EVN plus e-MERLIN observation. The upper panel shows the tapered image with a beam size of $9.27 \times 5.95$ mas, the rms noise is 0.01 mJy/beam. The lower panel shows the delta-model-fitted image with the beam size of $3.22 \times 1.14$ mas and the rms noise of 0.007 mJy/beam, the blue crosses show the location of components, the red asterisks indicate the Gaia position. The delta-model-fitted image only shows the most compact components, the component E3a and E3b is revealed at the delta-model-fitted image and the component X can not be recognised as it’s not matched between the cleaned and model-fitted images. All the images are produced with a natural weighting and taking the Gaia position as the reference point, the contours are at $3\sigma \times (-1, 1, 1.41, 2, 2.83, ...)$. 

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Figure 5: Model-fitting images of the phase calibrator J0056+1341 at 1.54 GHz (panel a and b) and 4.92 GHz (panel c). The images are produced using two-dimensional Gaussian model fitting with natural weights, with contours plotted as $3\sigma \times (-1, 1, 2, 4, 8, \ldots )$, where $\sigma$ is the root mean square (rms) noise. The black solid lines represent positive values and the red dashed lines represent negative values. The rms noise is 0.2 mJy/beam for both 1.54 and 4.92 GHz images. The model-fitting components are superimposed as yellow circles. The grey ellipses at the bottom left corner of each panel represent the full-width at half-maximum (FWHM) of the restoring beam. The grey lines between panels c and b indicate the corresponding components without the core-shift effect, i.e. the optically thin components.
Figure 6: **Constraints on the flux density factor** $b$ **and expansion factor** $\eta$ **with the adiabatic jet expansion model for I Zw 1.** The model is constrained on the radio flux density distribution along with the distance to the core, where the data points with positive and negative radius are the approaching and receding jet, respectively. The radio flux density is from clean components at 4.92 GHz, where only the bright components (marked with the blue and red circle) are used for least-square fitting, the components at radius $\sim 1$ and $\sim 10$ mas are not considered in the fitting. The blue and red solid line indicates best-fit results for approaching and receding jets, respectively, where the blue and red belt is the $1\sigma$ error.
Figure 7: **Jet (blue) and counter jet (red) based on the parameters of maximum likelihood and random sampling.** The blue and red solid lines based on the parameters: inclination angle $i = 87.6^\circ$, opening angle of jet precessing cone $\psi = 5.7^\circ$, position angle to the north anti-clockwisely $\chi = 101.4^\circ$, angular velocity $\Omega = 8.59$ deg/year and angle of terminal jet components with respect to the line of sight $\theta = -136^\circ$. 
Figure 8: **Marginalised and joint posterior probability distribution for the model parameters in the mcmc approach.** We only show four parameters: inclination angle $i$ in radians, opening angle of jet precessing cone $\psi$ in radians, position angle to the east $\chi$ in radians and precession period $\Omega$ in $\text{radian/year}$, additionally, the jet velocity was correlated with inclination angle $i$ in equation 9. The cross lines marker the values from a least-square fitting.
Figure 9: The radio flux density of I Zw 1 over a time interval of 37 years. The integrated radio flux densities and their uncertainties are taken from Table 2, where the data with the same observing band (approximately equal central frequencies) and arrays/sub-arrays are concatenated to show the variability.
Figure 10: **Wide-band radio spectrum of I Zw 1.** The integrated radio flux density measurements of I Zw 1 in five radio frequency bands between 1.4 and 15 GHz are shown, where the flux density and uncertainties are taken from Table 2. The blue dashed line is the model-fitting result with a power-law spectrum using all the data points presented here. The power-law slope (spectral index) is $-0.88$, the blue belt shows the 95% confidence intervals (0.10). The green and red dashed lines show the power-law fitting between 1.4 and 5 GHz datasets with similar size scales, i.e. 1.3~1.5 (red) and 4.3~5.3 (green), respectively, the green and red belts indicate their 95% confidence intervals, respectively.
Figure 11: The radio flux density of I Zw 1 over a collection area range from $\sim 0.04$ to $\sim 50$ arcsec. The integrated radio flux densities and uncertainties of I Zw 1 in L and C bands are shown, which are taken from Table 2. As I Zw 1 is not resolved in the given observations, the synthesised beams are taken to represent the collection area. The dashed lines and belts show power-law fittings and 95% confidence intervals, respectively, at L (red) and C-band (green). The intervals between L and C-band flux density represent the radio spectral index.