Event Horizon Telescope observations of the jet launching and collimation in Centaurus A

Jansen, Michael; Chatterjee, K.; Markoff, S.B.; Musoke, G.; Porth, O.; Yoon, D.; The Event Horizon Telescope Collaboration

DOI
10.1038/s41550-021-01417-w

Publication date
2021

Document Version
Final published version

Published in
Nature Astronomy

License
CC BY

Citation for published version (APA):
Jansen, M., Chatterjee, K., Markoff, S. B., Musoke, G., Porth, O., Yoon, D., & The Event Horizon Telescope Collaboration (2021). Event Horizon Telescope observations of the jet launching and collimation in Centaurus A. Nature Astronomy, 5, 1017-1028. https://doi.org/10.1038/s41550-021-01417-w
Event Horizon Telescope observations of the jet launching and collimation in Centaurus A

Michael Janssen1,2✉, Heino Falcke2, Matthias Kadler3, Eduardo Ros1, Maciek Wielgus4,5, Kazunori Akiyama4,6,7, Mislav Baloković8,9, Lindy Blackburn4,5, Katherine L. Bouman4,5,10, Andrew Chael11, Chi-kwan Chan12,13, Koushik Chatterjee14, Jordy Davelaar12,15,16, Philip G. Edwards17, Christian M. Fromm4,5,18, José L. Gómez19, Ciriaco Goddi4,5,20, Sara Issaoun12, Michael D. Johnson4,5, Junhan Kim10,12, Jun Yi Koay21, Thomas P. Krichbaum21, Jun Liu1, Elisabetta Liuzzo14, Sera Markoff14,23, Alex Markowitz24, Daniel P. Marrone12, Yosuke Mizuno18,25, Cornelia Müller12, Chunchong Ni26,27, Dominic W. Pesce4,5, Venkatesh Ramakrishnan28, Freek Roelofs2,29, Kazi L. J. Rygl10, Ilse van Bemmel29 and The Event Horizon Telescope Collaboration*

Very-long-baseline interferometry (VLBI) observations of active galactic nuclei at millimetre wavelengths have the power to reveal the launching and initial collimation region of extragalactic radio jets, down to 10–100 gravitational radii ($r_g \equiv GM/c^2$) scales in nearby sources. Centaurus A is the closest radio-loud source to Earth1. It bridges the gap in visible scales remarkably well. Furthermore, by the Event Horizon Telescope (EHT) with a nominal resolution of 25 microradians (mas) at a wavelength ($\lambda$) of 1.3 mm. For a black hole mass of $M = (5.5 \pm 3) \times 10^7 M_\odot$ (ref. 7), we are probing jet structures down to scales of ~200 gravitational radii $r_g \approx 0.6$ light days. It has recently become possible to model these scales with sophisticated general relativistic magnetohydrodynamics (GRMHD) simulations8, where jet ejection and their symbiotic relationship with accretion flows are simulated from first principles. We have observed Cen A in a six-hour-long track on 10 April 2017. The EHT, as a novel and heterogeneous high-frequency very-long-baseline interferometry (VLBI) array, poses unique calibration challenges. To obtain robust results, independent of assumptions made during the data calibration, we base our scientific analysis on two datasets, which we obtained from two independent calibration pipelines: rPI-CARD9 and EHT-HOPS10 ('Data reduction pipelines' in Methods). Figure 1 presents our reconstruction of the jet image structure derived from the EHT data using a regularized maximum likelihood method, next to the large-scale source morphology and the

1Max-Planck-Institut für Radioastronomie, Bonn, Germany. 2Department of Astrophysics, Institute for Mathematics, Astrophysics and Particle Physics (IMAPP), Radboud University, Nijmegen, The Netherlands. 3Lehrstuhl für Astronomie, Universität Würzburg, Würzburg, Germany. 4Black Hole Initiative (BHI), Harvard University, Cambridge, MA, USA. 5Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, USA. 6Massachusetts Institute of Technology Haystack Observatory, Westford, MA, USA. 7National Astronomical Observatory of Japan, Mitaka, Japan. 8Yale Center for Astronomy and Astrophysics, New Haven, CT, USA. 9California Institute of Technology, Pasadena, CA, USA. 10Princeton Center for Theoretical Science, Princeton University, Princeton, NJ, USA. 11Steward Observatory and Department of Astronomy, University of Arizona, Tucson, AZ, USA. 12Data Science Institute, University of Arizona, Tucson, AZ, USA. 13Anton Pannekoek Institute for Astronomy, University of Amsterdam, Amsterdam, The Netherlands. 14Department of Astronomy and Columbia Astrophysics Laboratory, Columbia University, New York, NY, USA. 15Center for Computational Astrophysics, Flatiron Institute, New York, NY, USA. 16Australia Telescope National Facility, CSIRO Astronomy and Space Science, Epping, New South Wales, Australia. 17Max Planck Institute for Gravitational Physics, Dwingeloo, The Netherlands. 18Max-Planck-Institut für Radioastronomie, Bonn, Germany. 19Rechenzentrum der Technischen Universität München, Garching bei München, Germany. 20Leiden Observatory—Albert Einstein Institute, Leiden, The Netherlands. 21Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan, ROC. 22Institute of Theoretische Physik, Goethe-Universität Frankfurt, Frankfurt, Germany. 23Instituto de Astrofísica de Andalucia-CSIC, Granada, Spain. 24Leiden Observatory—Albert Einstein Institute, Leiden, The Netherlands. 25Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan, ROC. 26Italian ALMA Regional Centre, INAF-Istituto di Radioastronomia, Bologna, Italy. 27Instituto de Astrofísica de Andalucía-CSIC, Granada, Spain. 28Leiden Observatory—Albert Einstein Institute, Leiden, The Netherlands. 29Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan, ROC. 22Italian ALMA Regional Centre, INAF-Istituto di Radioastronomia, Bologna, Italy. 21Institute of Astrophysics of Andalusia, Granada, Spain. 20Leiden Observatory—Albert Einstein Institute, Leiden, The Netherlands. 19Institute of Astronomy and Astrophysics, Academia Sinica, Taipei, Taiwan, ROC. 18Institute of Theoretische Physik, Goethe-Universität Frankfurt, Frankfurt, Germany. 17Max Planck Institute for Gravitational Physics, Dwingeloo, The Netherlands. 16Center for Computational Astrophysics, Flatiron Institute, New York, NY, USA. 15Center for Computational Astrophysics, Flatiron Institute, New York, NY, USA. 14Department of Astronomy and Columbia Astrophysics Laboratory, Columbia University, New York, NY, USA. 13Anton Pannekoek Institute for Astronomy, University of Amsterdam, Amsterdam, The Netherlands. 12Data Science Institute, University of Arizona, Tucson, AZ, USA. 11Steward Observatory and Department of Astronomy, University of Arizona, Tucson, AZ, USA. 10California Institute of Technology, Pasadena, CA, USA. 9National Astronomical Observatory of Japan, Mitaka, Japan. 8Yale Center for Astronomy and Astrophysics, New Haven, CT, USA. 7Massachusetts Institute of Technology Haystack Observatory, Westford, MA, USA. 6National Astronomical Observatory of Japan, Mitaka, Japan. 5Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA, USA. 4Black Hole Initiative (BHI), Harvard University, Cambridge, MA, USA. 3Lehrstuhl für Astronomie, Universität Würzburg, Würzburg, Germany. 2Department of Astrophysics, Institute for Mathematics, Astrophysics and Particle Physics (IMAPP), Radboud University, Nijmegen, The Netherlands. 1Max-Planck-Institut für Radioastronomie, Bonn, Germany. 2Department of Astrophysics, Institute for Mathematics, Astrophysics and Particle Physics (IMAPP), Radboud University, Nijmegen, The Netherlands. *A list of authors and their affiliations appears at the end of the paper. ✉e-mail: mjanssen@mpifr-bonn.mpg.de
similarly edge-brightened morphology of the Messier 87 (M87) jet on comparable gravitational scales. These images are convolved with Gaussian beams set by their respective nominal instrumental resolutions, as per standard practice in radio-interferometric imaging, to suppress possibly spurious fine-scale structures in the image model. The brightness temperatures $T$ (K) shown are related to flux densities $S$ in jansky (Jy) through the observing wavelength $\lambda$, Boltzmann constant $k$, and angular resolution element $\Omega$ as $T = \lambda^2 (2k_\text{B} \Omega)^{-1} S$. The $1.3\,\text{mm}$ Cen A jet has a narrow, collimated profile and exhibits one-sidedness, pronounced edge-brightening and a northwest–southeast brightness asymmetry. The approaching jet extends towards the northeast and the faint counterjet is directed southwards. The total compact flux density in our image is $\sim 2\,\text{Jy}$. The identification of the jet apex and black hole position (The position of the jet apex’ in Methods) is shown in the unconvolved image model of Fig. 2. We can use interferometer data with a high signal-to-noise ratio to super-resolve image features beyond the image model of Fig. 2. We have verified the robustness of the counterjet feature with synthetic data studies (Supplementary Fig. 1). The estimated jet position angle on the sky of $48^\circ \pm 5^\circ$ agrees with centimetre-wave VLBI observations. The centimetre-band data also constrain the inclination angle of the jet axis with respect to our line of sight to $\theta = 12^\circ - 45^\circ$, assuming that the jet does not bend along the line of sight.

The Cen A $\lambda 1.3\,\text{mm}$ jet exhibits three types of brightness asymmetry ($R$): between the jet and counterjet, the sheath and spine, and the northwest versus southeast ridgelines (‘Brightness asymmetries’ in Methods). We take the two bright radiating streams of the approaching jet and counterjet as jet ‘arms’ and denote the maximum intensity region along each arm as ‘ridgeline’. The jet-to-counterjet intensity ratio $R_{\text{jet} / \text{ct}}$ can naturally be explained for a relativistic outflow with an inclination angle $\theta \neq 90^\circ$, where jet emission will be Doppler boosted and counterjet emission de-boosted. We find $R_{\text{jet} / \text{ct}} \gtrsim 5$, which is in agreement with centimetre-wave VLBI observations and suggests that the initial acceleration of the jet occurs within the inner collimation region imaged in this study.

There is no jet spine emission in our image. With synthetic data studies, we found that spine emission exceeding $\sim 20\%$ of the sheath radiation intensity would be detectable, that is, $R_{\text{sh} / \text{sp}} > 5$ (Synthetic data imaging tests’ in Methods). The intensities of the brightest, central southeast and northwest jet components in the unconvolved image are $(32 \pm 8) \times 10^9$ K and $(20 \pm 4) \times 10^9$ K, respectively. The brightness ratio between these components follows as $R_{\text{sh} / \text{sp}} = 1.6 \pm 0.5$.

The collimation profile of the jet width $W$ follows a narrow expansion profile with distance to the apex $z$ as $W \propto z^{k}$ with $k = 0.33 \pm 0.05$ (Fig. 3). Resolution and potentially optical depth effects prevent us from pinning down the jet opening angle $\psi_{\text{jet}}$ at small $z$, where the jet converges towards the apex. We denote the boundary between the inner convergence region and the outer jet with a clearly defined collimation and easily traceable jet ridgelines as $z_{\text{ct}}$. For the brighter and straighter southeast arm, we have $W(z_{\text{ct}} \approx 32\,\mu\text{as}) \approx 25\,\mu\text{as}$, that is, the brightest jet component marks the boundary between the convergence and strongly collimated regions here (Fig. 2). If we assume the two jet ridgelines to meet at the apex, we find $\psi_{\text{jet}} \gtrsim 40^\circ$ as a conservative estimate. Factoring in the range of possible $\theta$ values yields $\psi_{\text{jet}} \gtrsim 10^\circ - 30^\circ$ for the intrinsic, deprojected opening angle (‘Collimation profile’ in Methods).

The M87$^{11}$ (NGC 4486, 3C 274, Virgo A), Markarian 501$^{12}$ and restarted 3C84 jets$^{13}$ also show strong edge-brightening and large initial opening angles on comparable scales seen in similar inclination angles of $\sim 18^\circ$. The expansion profile of Cen A lies in between the parabolic profile of M87 ($k = 0.5$) and the almost cylindrical profile of 3C84 ($k = 0.2$), which implies a strong confinement of the 3C84 jet by a shallow pressure gradient from the ambient medium. For the inner Cen A jet, this suggests strong magnetic collimation or the presence of external pressure and density gradients of $P_{\text{jet}} \propto z^{-4} \approx z^{-1.3}$ and $P_{\text{ct}} \propto z^{-1.4} \approx z^{-2.3}$ (‘Confinement by the ambient medium’ in Methods). Radiatively inefficient accretion flows alone, which are expected to operate in the M87, 3C84 and Cen A sub-Eddington low-luminosity active galactic nuclei (LLAGN) sources, have comparatively steeper pressure and density gradients. This may indicate the presence of winds, which are likely to be launched by this type of accretion flow. The noticeable similarity and prominence of edge-brightened jet emission in M87, 3C84 and Cen A suggests the dominance of jet sheath emission to be an emerging feature in LLAGN. In GRMHD simulations, the sheath
As interaction region between an accretion-powered outflow and the fast jet spine, which is potentially powered by the black hole spin. The mass-loaded sheath has a higher intrinsic emissivity compared with the evacuated spine. The same type of LLAGN-applicable GRMHD simulations also self-consistently develop a collimating helical magnetic field structure in the jet, which is confirmed observationally in many AGN. The dominating sheath emissivity and helical magnetic field structure provides a natural intrinsic explanation for the prevailing edge-brightening effect in LLAGN and can also explain the northwest–southeast brightness asymmetry. This model and alternative geometric explanations for the brightness asymmetries are discussed in ‘Brightness asymmetries’ in Methods.

The basic radiative properties of these jets can be analytically understood with a simple model, where particle and magnetic energy density equipartition is assumed, while the particle density decays with $z^{-2}$. Under these conditions, an optically thick and self-absorbed compact feature is expected (the core), whose position $z_{\text{core}}$ along the jet is frequency dependent with $z_{\text{core}} \propto \nu^{-1}$ (refs. 19,20). This radio core corresponds to the photosphere, where the optical depth $\tau(\nu)$ to photons at the observing frequency $\nu$ is unity. The jet is optically thick upstream and optically thin downstream. The photosphere moves closer to the jet apex at higher frequencies, until the point where either the launching point is reached near the horizon, or particle acceleration has not yet begun. The scale of a jet ‘nozzle’ emission cannot be smaller than the photon capture radius ($\tau(\nu)$), but future LLAGN-applicable GRMHD simulations also self-consistently develop a collimating helical magnetic field structure in the jet, which is confirmed observationally in many AGN. The dominating sheath emissivity and helical magnetic field structure provides a natural intrinsic explanation for the prevailing edge-brightening effect in LLAGN and can also explain the northwest–southeast brightness asymmetry. This model and alternative geometric explanations for the brightness asymmetries are discussed in ‘Brightness asymmetries’ in Methods.

The basic radiative properties of these jets can be analytically understood with a simple model, where particle and magnetic energy density equipartition is assumed, while the particle density decays with $z^{-2}$. Under these conditions, an optically thick and self-absorbed compact feature is expected (the core), whose position $z_{\text{core}}$ along the jet is frequency dependent with $z_{\text{core}} \propto \nu^{-1}$ (refs. 19,20). This radio core corresponds to the photosphere, where the optical depth $\tau(\nu)$ to photons at the observing frequency $\nu$ is unity. The jet is optically thick upstream and optically thin downstream. The photosphere moves closer to the jet apex at higher frequencies, until the point where either the launching point is reached near the horizon, or particle acceleration has not yet begun. The scale of a jet ‘nozzle’ emission cannot be smaller than the photon capture radius ($\tau(\nu)$), but future
spectral information is needed for a definitive confirmation. We show that \( \tilde{v} \) lies in the terahertz regime for Cen A based on the core shift that we can determine from our image, scaling relations with the M87 jet, and the spectral energy distribution of Cen A.

We take the distance from the brightest pixel in the image to the estimated position of the jet apex and obtain a core shift of \( \Delta x_{\text{core}} = 32 \pm 11 \mu\text{as} \). On the basis of this distance and the uncertain inclination angle, we estimate that an observing frequency of \( \tilde{v}_{\text{Cen A}} \approx 10-60 \text{THz} \) (The location of the black hole' in Methods) will reach the base of the jet at the black hole innermost stable circular orbit. A caveat is that we do not take the effect of the uncertain ambient medium into account in this simple picture.

Independently, we can use the above scaling relations to estimate the order of magnitude of \( \tilde{v}_{\text{Cen A}} \) by comparing the Cen A jet with M87, which has \( \tilde{v}_{\text{M87}} \approx 228 \text{GHz} \). For the centimetre jet radio core, a flux density of \( -1\text{Jy} \) is measured for both sources\cite{26,25}, which yields \( M_{\text{Cen A}} \approx 0.1 M_{\text{M87}} \) for the accretion onto the black hole and therefore \( \tilde{v}_{\text{Cen A}} \approx 26 \tilde{v}_{\text{M87}} \approx 6 \text{THz} \). The relation of accretion rates would constrain \( \tilde{v}_{\text{Cen A}} \) to be \( \approx 5 \times 10^{-5} M_{\text{Edd}} \) in terms of the Eddington accretion rate for an assumed radiative efficiency of 10%.

The core spectral energy distribution of Cen A peaks at \( \approx 10^{11} \text{Hz} \)\( ^{-}\), which may be equivalent to the submillimetre bump seen in Sagittarius A\( ^{+}\),\( -1\), and would further support our hypothesis. Observed correlations between the masses of accreting black holes and their X-ray and radio luminosities form the basis of a unified fundamental plane of scale-invariant black hole accretion. This scale invariance has been derived based on stellar-mass black holes and their X-ray and radio luminosities form the basis of a unified fundamental plane of scale-invariant black hole accretion.

Gains of co-located stations were solved based on a contemporaneous measurement of the total flux density \( S_{\nu} \) in Jy, which takes into account the gain and total noise power along a telescope's signal chain as a function of time \( t \) and frequency \( \nu \). On a baseline \( i-j \), correlation coefficients \( \xi_{ij} \) in units of thermal noise are calibrated to a physical radiation intensity scale of correlated flux density \( S_{\nu} \) through:

\[
S_{\nu}(t, \nu) = \frac{\sqrt{\text{SEFD}(t, \nu) \text{SEFD}(t, \nu)}}{\eta_{\nu}}
\]

where \( \eta_{\nu} \) is the quantization efficiency. For data recorded with 2-bit sampling, we have \( \eta_{\nu} = 0.88 \).

The gains of co-located stations were solved based on a contemporaneous measurement of the total flux density \( S_{\nu} \) in Jy, which takes into account the gain and total noise power along a telescope's signal chain as a function of time \( t \) and frequency \( \nu \).

Data reduction pipelines. The autocorrelation normalization, feed angle rotation, fringe fitting, bandpass calibration and a priori correction of atmospheric phase turbulence\cite{27} were performed independently by two pipelines: rPICARD\cite{28}, which is based on the Common Astronomy Software Applications (CASA) package\cite{29}, and EHT-HOPS\cite{30}, which is based on the Haystack Observatory Postprocessing System (HOPS)\cite{31}. Image Transport System (ITS)\cite{32}, the EHT-Interferometric Data Interchange Convention (FITS-IDI) and Mark 4 data. rPICARD uses the FITS-IDI product and converts it into the measurement set format. EHT-HOPS uses the Mark 4 data. Both software packages convert the calibrated data into the UVFITS format for further processing.

rPICARD performs an upstream correction for the feed rotation angle and uses station-based global fringe fitting based on an unpolaredized point source model to correct for phases, delays and rates consistently for the right-circular-polarization and left-circular-polarization signal paths\cite{33}. Atmospheric phase and residual delay variations are corrected within the expected coherence time by fringe fitting segmented data of each VLBI scan. The segmentation length is set by the signal-to-noise ratio (SNR) of each baseline.

For EHT-HOPS, the feed rotation angle is corrected after the fringe fitting together with an additional polarization calibration step, where complex polarization gain offsets are solved for. Delays and rates are found in a baseline-based fringe search and referenced to individual stations with a least-squares optimization\cite{34}.

Cen A has assumed the amount of Doppler boosting to be similar in both jets. The relation of accretion rates would constrain \( \tilde{v}_{\text{Cen A}} \) to be \( \approx 5 \times 10^{-5} M_{\text{Edd}} \) in terms of the Eddington accretion rate for an assumed radiative efficiency of 10%.

The core spectral energy distribution of Cen A peaks at \( \approx 10^{11} \text{Hz} \)\( ^{-}\), which may be equivalent to the submillimetre bump seen in Sagittarius A\( ^{+}\),\( -1\), and would further support our hypothesis. Observed correlations between the masses of accreting black holes and their X-ray and radio luminosities form the basis of a unified fundamental plane of scale-invariant black hole accretion. This scale invariance has been derived based on stellar-mass black holes and their X-ray and radio luminosities form the basis of a unified fundamental plane of scale-invariant black hole accretion.

Our findings suggest that the black hole shadow\cite{35} of Cen A would be visible in a bright, optically thin accretion flow at an observ-
Blind challenge. Similarly to the method used when the shadow of M87* was resolved by the EHT\textsuperscript{19}, we have carried out a blind imaging challenge before proceeding to the scientific analysis of the data. In this challenge, a number of individually reconstructed images of the source independently of each other. Early (not fully verified) low-band data from the EHT-HOPS pipeline was used, which had slightly larger amplitude gain errors from outdated a priori calibration parameters. Out of twelve total images, six had acceptable reduced $\chi^2_{\text{red}} < 2$ for the closure phases. These images were obtained with the eht-imaging and SMILI\textsuperscript{33,34} regularized maximum likelihood methods and the trimax\textsuperscript{43} and CASA\textsuperscript{44} CLEAN methods\textsuperscript{33-35}. The images that did not make the $\chi^2_{\text{red}}$ cut often showed spurious emission features and strong sidelobe structures.

Final imaging method. With the imaging challenge, we have established that different methods converge towards the same robust source structure (Supplementary Fig. 2), independent of shared human bias. Further imaging analysis of the pICARD and EHT-HOPS science release data was pursued with the final M87 eht-imaging script\textsuperscript{49}, which is based on application of a regularized maximum likelihood method that includes a maximum entropy term. Using a second-moment-based pre-calibration, LMT gains were stabilized with respect to the better constrained SMT amplitudes. As Cen A is sufficiently compact within the EHT beam, the short LMT-SMT baseline measures a Gaussian-like source structure. We have performed an initial self-calibration to a Gaussian with size $\theta_{\text{maj}} \times 8_{\text{maj}}$ at a position angle $\theta_{\text{maj}}$ and with a total flux of $S_c$. Here, $\theta_{\text{maj}}$ and $\theta_{\text{maj}}$ are the major and minor axis sizes of the Gaussian in radians. Any gains that were shared upon reasonable request. We have chosen for an eht-imaging reconstruction assumptions made during the data calibration. A variety of images that can be self-calibration steps. To solve for the image brightness distribution $Z$ with a regularized maximum likelihood method (employed by eht-imaging), we are minimizing

$$\sum_{\psi} \alpha_\psi \chi^2(\psi) = \sum_{\psi} \alpha_\psi (I(\psi) - Z(\psi)).$$

Here $D$ represents the collection of data terms, which are derived from the measured visibilities and have approximately Gaussian noise amplitudes, closure phases and log closure amplitudes. Corresponding to each data term, we have a goodness-of-fit function $\chi^2 = (Z - I)^2 / \sigma^2$ and relative weighting $\alpha_\psi = \sigma_{\text{sp}} \alpha_{\psi \sigma}$. We have performed four incremental imaging runs with subsequent self-calibration, over which we have increased the weight of each data term: $\alpha_\psi \rightarrow \alpha_\psi' \rightarrow \alpha_\psi'' \rightarrow \alpha_\psi''' \rightarrow \alpha_\psi'''' \rightarrow D$. Regularizer terms $\Lambda$ are included which impose additional assumptions on the model. We have imposed two regularization parameters: one for a maximum entropy method (MEM) term with weight $\beta_{\text{MEM}}$ and another one for the amount of compact flux $Z_c$ in the image with weight $\beta_{\text{c}}$. The MEM term minimizes the entropy of $Z$ with respect to a prior image $\Phi$, which results in a similarity between the two images for each pixel $i$. Here, we used $\lambda_{\text{MEM}} = -\sum_{i} \sum_{\psi} \sum_{\psi} \log (Z_i / \Phi_i)$. For the MEM prior image $\Phi$, we have chosen a Gaussian model oriented along the direction of the large-scale jet, which we also used as initialization for our imaging. It is expected that $Z_c < S_{\text{maj}}$ as a substantial portion of the flux measured by ALMA can come from different emission mechanisms and larger scales outside of the EHT field of view. In fact, the $-$150 m JCMT-SMA baseline sees a flux density of about 3 Jy and at 2 km, ALMA-APEX recovers only 4 Jy. For M87*, the EHT measured $Z_c = S_{\text{maj}} / 2$ (ref. \textsuperscript{50}).

The numerical values of the final imaging parameters are given in Supplementary Table 1. Optimal parameters were chosen based on an empirical minimization of $\chi^2_{\text{red}}$ median stations gain $A_{\text{median}}$ from self-calibration and patches of spurious flux in the image. In addition, we took the similarity of image reconstructions from the pICARD and EHT-HOPS data for a given set of parameters into account to avoid overfitting to data peculiarities that result from assumptions made during the data calibration. A variety of images that can be reconstructed with various combinations of the free imaging parameters can be shared upon reasonable request. We have chosen for an eht-imaging reconstruction of the pICARD data for our final image, as this imaging method and dataset have been studied most extensively.

Our images are shown in units of brightness temperature $T(B)$, which is related to the flux density $S$ by the observing wavelength $\lambda$, Boltzmann constant $k$, and angular resolution element $\Delta \Omega = \pi \times 4$. Fundamental data properties and fits of the final image model to the data are shown in Supplementary Fig. 4. In Supplementary Fig. 5, we show the measured amplitudes projected along and perpendicular to the jet position angle. Along the jet axis, amplitudes fall off quickly at long projected baseline lengths, indicating the absence of substructures along the jet. Perpendicular to the jet, ‘bouncing’ amplitudes out to large projected baseline lengths occur, due to the strong intensity gradients across the transverse jet profile.

Synthetic data imaging tests. We have used the SYMBA software\textsuperscript{51} to perform imaging studies based on simulated observations. Given an input source model $\mathcal{M}$, SYMBA follows the entire EHT signal path to predict which source structure $Z$ matches the input model $\mathcal{M}_{\text{final}}$. Then, we have removed the counterjet and emission features at large distance to the apex $z$ from $\mathcal{M}_{\text{final}}$ to verify that these do not spuriously appear in our simulated observation.

Furthermore, we have performed three synthetic data tests (Supplementary Fig. 1). First, a control study to demonstrate that the output reconstruction from SYMBA correctly matches the input model $\mathcal{M}_{\text{final}}$. Then, we have removed the counterjet and emission features at large distance to the apex $z$ from $\mathcal{M}_{\text{final}}$ to verify that these do not spuriously appear in our simulated observation.

Jet structure analysis. This section describes how we extract fundamental jet parameters from our image based on geometric arguments.

The position of the jet apex. We can empirically determine the approximate position of the jet apex, where the jet and counterjet are being launched, from the resolution images in Fig. 1. A notable bend in the jet appears at the apex, but a tentative merge of the two arms can be seen. The upper arm (region I in the figure) exhibits a strong bend, while the lower arm (IV) remains mostly straight. We note that a similar structure, where one jet arm appears to be straighter than the other one, is also present in the M87 jet\textsuperscript{38}. The second consideration is the symmetry between the approaching jet and the counterjet. We note that there is no clear correspondence between individual features in the jet and counterjet. The counterjet appears straight with two components in the upper region (II) and one component in the lower region (III). As the apex must be upstream of the counterjet, the closest component of the receding jet to the approaching jet constrains how far upstream of the approaching jet the apex position can be. In fact, the position we assume for the apex based on the first consideration, where the streamlines of the approaching jet converge, lies halfway between the radio core in region I and the closest counterjet component in region II. It should be noted that a simple extrapolation of only the edge-brightened approaching jet would place the apex well inside the faint counterjet region.

On the basis of the robustness of our image reconstructions with different datasets, software packages and imaging parameters, we assume a positional uncertainty of 5 mas for the robust features of the image model, which is in agreement with the width of the jet ridgelines. Taking all constraints on the apex location into account, we estimate an uncertainty of 10 μas on the position.

For the determination of $z_c$, the pixel and jet apex position uncertainties are added in quadrature. On the basis of possible jet apex positions within the estimated uncertainty, we fit the $\mathcal{M}$ on its $z_c$ jet profile multiple times and derive a systematic error of $\pm 0.06$ on $k$. When we used image model convolved with the nominal resolving beam, we obtain $k = 0.35$ with a statistical error of ±0.2.

Brightness asymmetries. The jet–counterjet asymmetry is most likely caused by relativistic boosting. We can calculate the $R_{\text{jet}}$ brightness ratio by taking the average image flux density within 50×100 μas rectangular regions on opposite sides of the apex. This ratio has to be interpreted with care, since the two regions may be at different distances to the jet apex. Moreover, counterjet radiation may be dominated by the inner jet–counterjet difference, which arises from asymmetries in the jet launching process and the ambient medium\textsuperscript{59,60}. If we assume the intrinsic emissivity to be the same in the jet sheath and spine, beaming effects can be invoked to explain observed differences in brightness across the jet. We note that the intrinsic emissivity of jet sheath is probably larger than that of the spine, as mentioned in the main text. The simplifying assumption of identical intrinsic emissivities can nonetheless be used to derive straightforward estimates for jet velocity components and the inclination angle $\theta$, since Doppler boosting is expected to have a considerable contribution to the observed source structure. If the inclination angle $\theta$ is not too small, a substantial portion of the spine emission may be beamed away from the line of sight. If the sheath and spine emissivities are $\mathcal{Q}_{\text{sh}}$ and $\mathcal{Q}_{\text{sp}}$, respectively, the ratio of $I_{\text{sh}}$ sheath and $I_{\text{sp}}$ spine intensities in a continuous jet follows as

$$R_{\text{jet}} = \int_{\text{jet}} \frac{1}{\text{jet}} \left[ \frac{1 - \beta_{\text{sh}}^2 (1 - \beta_{\text{sh}}^2 \cos \theta)^2}{1 - \beta_{\text{sp}}^2 (1 - \beta_{\text{sp}}^2 \cos \theta)^2} \right] \, d\psi.$$
with $\alpha(\nu/c\nu)$ as the spectral index of the optically thin jet components. Assuming a typical spectral index of $\alpha = -0.7$ and identical intrinsic emissivities, we can constrain the sheath and spine velocities with equation (3) and $\mathcal{R}_{\text{col}} > 5$ to
\begin{equation}
(1 - \beta)^{-0.5} \left[ 1 - \beta \cos(\theta) \right] > 1.8 \left( 1 - \beta_{\text{she}}^{-0.5} \right) \left( 1 - \beta \cos(\theta) \right).
\end{equation}

For a full three-dimensional picture of a jet, where we assume the sheath to be symmetric in the $\beta$ direction around the spine in a cylindrical coordinate system, different spine and sheath emissivities, due to beaming or intrinsic effects, cannot, on their own, explain edge-beaming. First, we discuss a common interpretation related to pathlength differences. As this only works in optically thin regions, we put the presence of helical magnetic fields forward as the most likely, intrinsic explanation for edge-beaming in LLAGN. We then discuss more exotic scenarios, of a rotating or asymmetric jet, which might be tested through future observations.

In the optically thin jet regions, the integrated column density along sightlines through the jet at different distances from its axis (centre versus edges) can be used to explain edge-beaming. These are sightlines, that across the transverse extent of the jet, enter the jet at different locations. The sightlines first pass through the near side of the jet and exit again at the other side of the jet, the far side. If we assume the absence of intrinsic spine emissivity (due to weak mass loading or beaming of radiation into a narrow cone away from the line of sight), the observed radiation will be produced by a sheath of thickness $\Delta R$. For a line sight that goes exactly through the centre of the jet, we pass twice through the sheath, which would amount to a pathlength of $2\Delta R/\sin \theta$, where the pathlength is short enough to locally approximate the jet as a cylinder. For a local jet radius $R$, the column density along a sightline through the edge of the jet will be larger by a factor of $\beta_{\text{she}}^{-1/2}$ (ref. 2). Here we have neglected changes in emissivity as sightlines pass through material at different distances to the jet apex. This simple model is capable of explaining edge-beaming in optically thin jet regions, where radiation along longer pathlengths accumulates. For Cen A, this would imply a thin radiating sheath with $\Delta R < 0.04 R_0$.

However, the edge-beaming in Cen A extends to the presumably optically thick radio core, suggesting that different physics are at play in this jet. The likely presence of a helical magnetic field$^{2,0}$ combined with a rotating sheath and the inclination angle $\theta$, can lead to favourable/unfavourable pitch angles that maximize/minimize the synchrotron emissivity along the edges/centre of the jet. For a power-law distribution of electrons with index $p$, where in the rest frame of the jet, the electron density varies as $\nu^{-p}$, the synchrotron emissivity coefficient in the rest frame scales as $j_{\nu} \propto |\sin \chi|^{(p+1)/2} \nu^{-(p+1)/2}$ (refs. 4,5). Here, $B$ is the magnetic field strength, $\chi$ is the angle between the magnetic field and line of sight, and $\nu$ is the radiation frequency. The corresponding absorption coefficients scale as $\kappa_{\nu} \propto |\sin \chi|^{(p+1)/2} \nu^{-(p+1)/2}$ (refs. 4,5). It can be seen that no asymmetries in $\chi$ would arise across the transverse jet profile for a purely poloidal $(B)$ magnetic field. The edge-beaming is maximized for perpendicular angles $\chi$ between the line of sight and magnetic field at the jet edges, while the magnetic field is oriented parallel to the line of sight in the centre of the jet. In future work, we will study the polarimetric properties of the jet with the EHT to test this hypothesis as an explanation for the edge-beaming. To get a handle on $\chi$, it will be necessary to narrow down the inclination angle $\theta$ and jet velocity with monitoring observations to take relativistic aberration into account.

For optically thick jet regions upstream of the radio core, the relativistic boosting is sensitive to the shape of the emitting region and less sensitive to the Doppler factor$^{1}$. In the presence of a fast helical jet flow and $\theta > 0$, part of the jet will rotate towards the observer and the other part will rotate in the opposite direction on the sky. Beyond the initial jet launching region, the jet is strongly collimated and the viewing angle to the jet edges will be very close to $\theta$. For a flow with toroidal and poloidal components, we denote the angle of the helical velocity component $\beta$, with respect to the poloidal direction along the line of sight with $\phi_{\text{obs}}$. For two identically shaped, optically thick radio core components of intensity $I$, at the southeast jet edge and $L$ at the northwest edge, we thus have
\begin{equation}
\mathcal{R}_{\text{col}} \equiv \frac{I_1}{I_0} = \frac{1 - \beta \cos(\theta) - \phi_{\text{obs}}}{1 - \beta \cos(\theta) + \phi_{\text{obs}}}.
\end{equation}

For an anticlockwise jet rotation and $\mathcal{R}_{\text{col}} \approx 1.6$, we get the weak constraint of
\begin{equation}
1.3(\cos(\theta - \phi_{\text{obs}}) - \cos(\theta + \phi_{\text{obs}}) \approx 0.3 h^{-1}.
\end{equation}

When the bulk velocities of the northwest and southeast jet sheaths are known, $\phi_{\text{obs}}$ and subsequently $\beta$, can be determined$^{29}$. We note that the small linear scales resolved by the EHT in Cen A uniquely allow us to track relativistic dynamics across this source with future observations.

In an alternative scenario, this tentative northwest–southwest brightness asymmetry seen in Cen A could be explained with two distinct jet components having different velocities or different inclinations angles with respect to the line of sight.

In this work, we have interpreted the edge-brightening in terms of a naturally emerging spine–sheath jet structure in LLAGN, based on results from GRMHD simulations that are applicable to those type of sources. However, the same phenomenon is also observed in more powerful AGN; for example, Cygnus A$^{30}$, where an accretion flow operating at ~1% of the Eddington limit is unlikely to be radiatively inefficient$^{1}$.

Collimation profile. Following the northwest and southeast jet ridgelines, we bin distance values to the jet apex into intervals of 10$\mu$as in size. Within each bin, we select the brightest pixel to obtain the central location along the ridge. We impose a statistical uncertainty of 5$\mu$as on distances $\zeta$ in accordance with the width of the jet ridgelines in our image model. The width $W$ of the jet is taken as the distance between the two jet arms. The profile of our image is shown in Fig. 3 together with the corresponding average opening angle computed from the jet width as a function of distance to the apex.

Resolution limitations prevent us from tracing down the exact value of the initial jet opening angle $\psi_{\text{she}}$, near the apex, where the analysis of binned distance values becomes uncertain. Nonetheless, we can derive an upper limit on $\psi_{\text{she}}$ with a simple geometric argument: the jet has a clearly defined collimation region beyond some distance from the apex, at $\zeta > z_{\text{sh}}$. To estimate $z_{\text{sh}}$, we use the southeast jet arm, as it is brighter, straighter, and has a more clearly identifiable compact brightness core. If we now assume that the jetstream converges monotonically towards the apex for $\zeta < z_{\text{sh}}$, and that the apex itself does not correspond to an extended region, we have
\begin{equation}
\psi_{\text{she}} \geq 2 \arctan \left( \frac{W_{\text{sheal}}}{2 \zeta_{\text{sh}}} \right).
\end{equation}

The jet remains collimated out to kiloparsec scales and contains multiple particle acceleration sites in a knotted structure$^{10,11}$. The source is a well-suited laboratory for models of AGN feedback$^{12,13}$ and the creation of ultrahigh-energy cosmic rays$^{14}$. Confinement by the ambient medium. Analytic theory for axisymmetric, relativistic, Poynont-dominated outflows can be used to derive exact asymptotic solutions for the influence an ambient medium on the collimation of a jet. One can show that in the presence of external pressure gradient $P_\text{ext}(z) = P_\text{ext}(z)$, the jet expansion profile as a function of distance along the jet axis $z$ follows
\begin{equation}
W(z) = C_4 \frac{\nu^{2/3}}{2 \pi} \left( \nu z C_3 + \frac{\nu}{2 \pi} \sin S \right) \approx k \frac{c^2}{z},
\end{equation}

in a simplified form, with $C_4$ a numerical constant. At large $z$ and for a shallow external pressure gradient with $k < 2$, we obtain
\begin{equation}
W(z) = C_1 \frac{\nu^{2/3}}{2 \pi} \left( \nu z C_3 + \nu \frac{\pi}{2} \sin S \right) \approx k \frac{c^2}{z},
\end{equation}

for $S(z) = C_2 e^{-z/2}$. $C_1$, $C_2$, $C_3$, $C_4$, and $C_5$ are numerical constants. Equation (10) shows that the ambient pressure will confine the jet into a $W(z)$ profile with $k = 2$. In addition, oscillations along the jet boundary can occur in a non-equilibrium state for $C_4 \neq \gamma<0$ (ref. 29). The location of the black hole. Given a measurement of the core shift $z_{\text{obs}}$ with respect to the black hole, we can gauge the observing frequency $\nu$, which corresponds to a small self-absorbed nozzle region at the footprint of the jet$^{15}$. This region corresponds to a peak or break from a jet-dominated flat radio spectrum as it is the smallest region where particle acceleration can occur. The minimum scale where a jet can be launched by a black hole is given by the innermost stable circular orbit. The size of the emission region of this nozzle would be given by the photon capture radius. Thus, we can estimate $\nu$ as
\begin{equation}
\nu = \frac{\nu_{\text{obs}} \theta_{\text{core}} \nu_{\text{obs}}}{\sqrt{27} h},
\end{equation}

where

\begin{equation}
(1 - \beta_{\text{she}})^{-0.5} \left[ 1 - \beta \cos(\theta) \right] > 1.8 \left( 1 - \beta_{\text{she}}^{-0.5} \right) \left( 1 - \beta \cos(\theta) \right).
\end{equation}

(4)

\begin{equation}
(1 - \beta)^{-0.5} \left[ 1 - \beta \cos(\theta) \right] > 1.8 \left( 1 - \beta_{\text{she}}^{-0.5} \right) \left( 1 - \beta \cos(\theta) \right).
\end{equation}

(5)

\begin{equation}
1.3 \cos(\theta - \phi_{\text{obs}}) - \cos(\theta + \phi_{\text{obs}}) \approx 0.3 h^{-1}.
\end{equation}

(6)
In this expression, $M$ is the mass of the black hole and $D$ the distance from the black hole to the observer. With the derived scaling relation of $\nu \propto M^{-1.37}D_{17}^{-0.87}$, we can relate the black frequencies of two sources if their accretion rates or jet properties are known. Here, $\dot{M}$ is the black hole accretion rate and $\nu$ is the observed flat-spectrum radio flux density. In particular, if we assume for two sources to share the same basic intrinsic jet properties and orientation with respect to Earth, we have

$$\frac{\nu_2}{\nu_1} = \left( \frac{\dot{M}_1}{\dot{M}_2} \right)^{17/16} \left( \frac{D_1}{D_2} \right)^{0.87/0.87}.$$  \hspace{1cm} (12)

While these expressions are strictly speaking only true for a filled conical jet, they appear to describe the emission from the jet sheath and its basic scaling properties reasonably well\textsuperscript{116–123} and allows one to make a first-order estimate of the characteristic radio frequency of near-horizon emission.

We have used the above equations to estimate the accretion rate of Cen A to the one of M87 based on the assumption of a similar coupling between SMBH inflows and jet power. External Faraday rotation effects and a generally variable core luminosity makes the determination of jet accretion rates\textsuperscript{48, 59}, which should thus be taken as only an order-of-magnitude estimate. It is, however, worth pointing out that the black hole growth rate measured over cosmic timescales from X-ray cavity fluxes from the jet radio lobes is $10^{-7} M_\odot$ yr$^{-1}$ for both Cen A and M87\textsuperscript{50}.

Alternative interpretations for the brightest jet features. In this work, we have interpreted the brightest jet features as radio cores, which mark the transition region between upstream synchrotron self-absorbed jet regions and downstream optically thin areas. In our image, we are able to resolve the self-absorbed region between the putative radio core and jet apex, which coincides with the location of the SMBH and its accretion disk. With current telescopes, the radio core and upstream region remains unresolved for most AGN (see Table 2 in ref. \textit{for example}).

The radio core interpretation of the brightest jet features seems most plausible given our data. On the basis of simple analytical jet theory, a bright radio core is expected to be present in VLBI images. Radio cores are typically seen in sources similar to Cen A and the core shift typically follows the standard $\nu-$ relation in most sources\textsuperscript{51}. In fact, special circumstances have to be invoked to explain the absence of radio cores in VLBI images. For example, obscuration by an optically thick region in the foreground. We do think that this is a likely scenario for most sources\textsuperscript{89}. In fact, special circumstances have to be invoked to explain the absence of radio cores in VLBI images. For example, obscuration by an optically thick region in the foreground. We do think that this is a likely scenario for most sources\textsuperscript{89}. It should be noted that the image is dominated by the brightest, compact jet features, which would be computed in Cen A agrees with the core SED of the source and fundamental plane of black hole activity. Mon. Not. R. Astron. Soc. 345, 1057–1076 (2003).

Falcè, H., Körding, E. & Markoff, S. A scheme to unify low-power accreting black holes. Astron. Astrophys. 414, 895–903 (2004).

Neumayer, N. The supermassive black hole at the heart of Centaurus A: revealed by the kinematics of gas and stars. Publ. Astron. Soc. Aust. 27, 449–456 (2010).

Chatterjee, K., Li, M., Tchekhovskoy, A. & Markoff, S. B. Accelerating AGN jets to parsec scales using general relativistic MHD simulations. Mon. Not. R. Astron. Soc. 490, 2206–2218 (2019).

Janssen, M. et al. rIPCARD: A CASA-based calibration pipeline for VLBI data. Calibration and imaging of 7 mm VLBA observations of the AGN jet in M 87. Astron. Astrophys. 626, A75 (2019).

Blackburn, L. et al. EHT-HOPS pipeline for millimeter VLBI data reduction. Astrophys. J. 882, 23 (2019).

Kim, J.-Y. et al. The limb-brightened jet of M87 down to the 7 Schwarzschild radii scale. Astron. Astrophys. 616, A188 (2018).

Piner, B. G., Pant, N., Edwards, P. G. & Wiik, K. Significant limb-brightening in the inner parsec of Markarian 501. Astrophys. J. Lett. 690, L31–L34 (2009).

Giovannini, G. et al. A wide and collimated radio jet in 3C48 on the scale of a few hundred gravitational radii. Nat. Astron. 2, 472–477 (2018).

Narayan, R., Mahadevan, R. & Quataert, E. Black hole accretion disks (eds Abramowicz, M. A. et al.) 148–182 (Cambridge Univ. Press, 1998).

Blandford, R. D. & Payne, D. G. Hydromagnetic flows from accretion disks and the production of radio jets. Mon. Not. R. Astron. Soc. 199, 883–903 (1982).

Blandford, R. D. & Znajek, R. L. Electromagnetic extraction of energy from Kerr black holes. Mon. Not. R. Astron. Soc. 179, 433–456 (1977).

Gabuzda, D. Evidence for helical magnetic fields associated with AGN jets and the action of a cosmic galaxy. Galaxies 7, 5 (2018).

Blandford, R. D. & Königl, A. Relativistic jets as compact radio sources. Reviews. J. 232, 34–48 (1999).

Falcè, H. & Biermann, P. L. The jet-disk symbiosis. I. Radio to X-ray emission models for quasars. Astron. Astrophys. 293, 665–682 (1995).

Lobanov, A. P. Ultracompact jets in active galactic nuclei. Astron. Astrophys. 330, 79–99 (1998).

Romero, G. E., Boettcher, M., Markoff, S. & Tavecchio, F. Jet orientation in active galactic nuclei and microquasars. Space Sci. Rev. 207, 5–61 (2017).

Heinz, S. & Sunyaev, R. A. The non-linear dependence of flux on black hole mass and accretion rate in core-dominated jets. Mon. Not. R. Astron. Soc. 343, L59–L64 (2003).

Lucchini, M. et al. Correlating spectral and timing properties in the evolving jet of the micro blazar MAXI J1836–194. Mon. Not. R. Astron. Soc. 501, 5910–5926 (2020).

Hada, K. et al. An origin of the radio jet in M87 at the location of the central black hole. Nature 477, 185–187 (2011).

Event Horizon Telescope Collaboration et al. First M87 event Horizon Telescope Results. I. The shadow of the supermassive black hole. Astrophys. J. Lett. 875, L1 (2019).

Walker, R. C., Hardee, P. E., Davies, F. B., Ly, C. & Junor, W. The structure and dynamics of the subparsec jet in M87 based on 50 VLBA observations over 17 years at 43 GHz. Astrophys. J. 855, 128 (2018).

Kuo, C. Y. et al. Measuring mass accretion rate onto the supermassive black hole in M87 using Faraday rotation measure with the submillimeter array. Astrophys. J. Lett. 783, L3 (2014).

Abdo, A. A. et al. Fermi large area telescope view of the core of the radio galaxy Centaurus A. Astrophys. J. 719, 1433–1444 (2010).

Falcè, H. et al. Systematic measurement of Sagittarius A* from 20 centimeters to 1 millimeter and the nature of the millimeter excess. Astrophys. J. 499, 731–734 (1998).
the Delaney Family John A. Wheeler Chair at Perimeter Institute; Dirección General de Asuntos del Personal Académico-Universidad Nacional Autónoma de México (DGAPA-UNAM, projects IN112147 and IN112820); the EACOA Foundation of the East Asia Core Obser.

This paper makes use of the following ALMA data: ADS/JAO.ALMA#2016.1.01198.V.

According to the Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the original work, and indicate if changes were made. This license is an Attribution-ShareAlike license.

The authors declare no competing interests.
The Event Horizon Telescope Collaboration

Kazunori Akiyama, Antxon Alberdi, Walter Alef, Juan Carlos Algabe, Richard Anantua, Keiichi Asada, Rebecca Azulay, Anne-Kathrin Baczkó, David Baill, Mislav Baloković, John Barrett, Bradford A. Benson, Dan Bintley, Lindy Blackburn, Raymond Blundell, Wilfred Boland, Katherine L. Bouman, Geoffrey C. Bower, Hope Boyce, Michael Bremer, Christiaan D. Brinkerink, Roger Brissenden, Silke Britzen, Avery E. Broderick, Dominique Broguiere, Thomas Bronzwaer, Do-Young Byun, John E. Carlstrom, Andrew Chael, Chi-kwan Chan, Chami Chatterjee, Shami Chatterjee, John E. Conway, James M. Cordes, Thomas M. Crawford, Geoffrey B. Crew, Alejandro Cruz-Osorio, Yuzhu Cui, Jordy Davelaar, Mariafelicia De Laurentis, Roger Deane, James M. Cordes, Thomas M. Crawford, Geoffrey B. Crew, Alejandro Cruz-Osorio, Yuzhu Cui, Jordy Davelaar, Mariafelicia De Laurentis, Roger Deane, Jessica Dempsey, Gregory Desvignes, Jason Dexter, Sheperd S. Doeleman, Ralph P. Eatough, Joseph Farah, Heino Falcke, Vincent L. Fish, Ed Fomalont, H. Alyson Ford, Raquel Fraga-Encinas, Per Friberg, Christian M. Fromm, Antonio Fuentes, Peter Galison, Charles F. Gammie, Roberto García, Zachary Gelles, Olivier Gentaz, Boris Geogiev, Ciriac Goddi, Roman Gold, José L. Gómez, Arturo I. Gómez-Ruiz, Minfeng Gu, Mark Gurwell, Kazuhiro Hada, Daryl Haggard, Michael H. Hecht, Ronald Hesper, Elizabeth Himwich, Luis C. Ho, Mareki Honma, Chih-Wei L. Huang, Lei Huang, David H. Hughes, Shiro Ikeda, Makoto Inoue, Sara Issaoun, David J. James, Buell T. Jannuzi, Michael Janssen, Britton Jeter, Wu Jiang, Alejandra Jimenez-Rosales, Michael D. Johnson, Svetlana Jorstad, Taehyun Jung, Mansour Karami, Ramesh Karuppusamy, Tomohisa Kawashima, Garrett K. Keating, Mark Kettens, Dong-Jin Kim, Jae-Young Kim, Junhan Kim, Jongsoo Kim, Motoki Kino, Jun Yi Koay, Yutaro Kofuji, Thomas P. Krichbaum, Cheng-Yu Kuo, Tod R. Lauer, Sang-Sung Lee, Aviad Levis, Yan-Rong Li, Zhiyuan Li, Michael Lindqvist, Rocco Lico, Greg Lindahl, Jun Liu, Kuo Liu, Elisabetta Liuzzo, Wen-Ping Lo, Andrei P. Lobanov, Laurent Loinard, Colin Lonsdale, Ru-Sen Lu, Nicholas R. MacDonald, Jirong Mao, Nicola Marchili, Sera Markoff, Daniel P. Marrone, Alan P. Marscher, Iván Martí-Vidal, Satoki Matsushita, Lynn D. Matthews, Karl M. Menten, Izumi Mizuno, Yosuke Mizuno, James M. Moran, Kotaro Moriyama, Monika Moscibrodzka, Cornelia Müller, Gibwa Musoke, Alejandro Mus Mejías, Hiroshi Nagai, Neil M. Nagar, Masanori Nakamura, Ramesh Narayan, Naiman Narayan, Iniyi Natarajan, Antonios Nathanail, Joey Neilsen, Roberto Neri, Chunchong Ni, Aristeidis Noutsos, Michael A. Nowak, Hiroki Okino, Héctor Olivares, Gisela N. Ortiz-León, Tomoaki Oyama, Feryal Özel, Daniel C. M. Palumbo, Jongho Park, Nimesh Patel, Ue-Li Pen, Dominic W. Pesce, Vincent Piétu, Richard Plambeck, Aleksandar PopStefanić, Oliver Porth, Felix M. Pütz, Ben Prathee, Jorge A. Preciado-López, Dimitrios Psaltis, Hung-Yi Pu, Venkatesh Ramakrishnan, Ramprasad Rao, Mark G. Rawlings.
Letters Nature Astronomy

Alexander W. Raymond4,5, Luciano Rezzolla18,107,108, Angelo Ricarte4,5, Bart Ripperda16,109, Freek Roelofs2,5, Alan Rogers6, Eduardo Ros1, Mel Rose12, Arash Roshaninesh12, Helge Rottmann1, Alan L. Roy1, Chet Ruszczycy6, Kazi L. J. Ryg122, Salvador Sánchez110, David Sánchez-Argüelles69,70, Mahito Sasada52,111, Tuomas Savolainen112,113, F. Peter Schloerb97, Karl-Friedrich Schuster40, Lijing Shao1,75, Zhiqiang Shen4,49, Des Small29, Bong Won Sohn42,43,114, Jason SooHoo6, He Sun10, Fumie Tazaki52, Alexandra J. Tetarenko35, Paul Tiede26,27, Remo P. J. Tilanus212,20,115, Michael Titus6, Pablo Torne1,110, Tyler Trent12, Efthalia Traianou1, Sascha Trippe116, Ilse van Bemmel29, Huib Jan van Langevelde29,117, Daniel R. van Rossum2, Jan Wagner1, Derek Ward-Thompson18, John Wardle119, Jonathan Weintroub4,5, Norbert Wex1, Robert Wharton1, Maciek Wielgus4,5, George N. Wong66, Qingwen Wu120, Doosoo Yoon14, André Young2, Ken Young2, Ziri Younis18,121, Feng Yuan48,71,122, Ye-Fei Yuan123, J. Anton Zensus1, Guang-Yao Zhao19 and Shan-Shan Zhao48.

---

20Department of Physics, Faculty of Science, University of Malaya, Kuala Lumpur, Malaysia. 21Department d'Astronomie et Astrophysique, Faculté de Sciences, Université de Valenciennes, Valenciennes, France. 22Fermi National Accelerator Laboratory, Batavia, IL, USA. 23Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL, USA. 24East Asian Observatory, Hilo, HI, USA. 25Nederlandse Onderzoekschool voor Astronomie (NOVA), Leiden, The Netherlands. 26Institute of Astronomy and Astrophysics, Academia Sinica, Hilo, HI, USA. 27Department of Physics, McGill University, Montreal, Quebec, Canada. 28McGill Space Institute, McGill University, Montreal, Quebec, Canada. 29Institut de Radioastronomie Millimétrique, Saint Martin d'Hères, France. 30Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada. 31Korea Astronomy and Space Science Institute, Daejeon, Republic of Korea. 32University of Science and Technology, Daejeon, Republic of Korea. 33Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL, USA. 34Department of Physics, University of Chicago, Chicago, IL, USA. 35Enrico Fermi Institute, University of Chicago, Chicago, IL, USA. 36Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca, NY, USA. 37Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, People's Republic of China. 38Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, Nanjing, People's Republic of China. 39Physics Department, Fairleigh Dickinson University, Teaneck, NJ, USA. 40Department of Physics, University of Malaya, Kuala Lumpur, Malaysia. 41Letters Nature Astronomy.

---

1017–1028 | www.nature.com/natureastronomy | OCTOBER 2021 VOL 5

---

1027

---

1027
Leiden, The Netherlands. 119 Jeremiah Horrocks Institute, University of Central Lancashire, Preston, UK. 120 Physics Department, Brandeis University, Waltham, MA, USA. 121 School of Physics, Huazhong University of Science and Technology, Wuhan, Hubei, People’s Republic of China. 122 Mullard Space Science Laboratory, University College London, Surrey, UK. 123 School of Astronomy and Space Sciences, University of Chinese Academy of Sciences, Beijing, People’s Republic of China. 124 Astronomy Department, University of Science and Technology of China, Hefei, People’s Republic of China.