An energetic hot wind from the low-luminosity active galactic nucleus M81*

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For most of their lifetime, super-massive black holes (SMBHs) commonly found in galactic nuclei obtain mass from the ambient medium at a rate well below the Eddington limit1, which is mediated by a radiatively inefficient, hot accretion flow2. Both theory and numerical simulations predict that a strong wind must exist in such hot accretion flows3–6. The wind is of special interest not only because it is an indispensable ingredient of accretion but also, perhaps more importantly, because it is believed to play a crucial role in the evolution of the host galaxy via the so-called kinetic mode active galactic nucleus feedback7,8. Observational evidence for this wind, however, remains scarce and indirect9–12. Here we report the detection of a hot outflow from the low-luminosity active galactic nucleus in M81, based on Chandra high-resolution X-ray spectroscopy. The outflow is evidenced by a pair of Fe xxvi Lyα lines redshifted and blueshifted at a bulk line-of-sight velocity of \( \pm 2.8 \times 10^7 \) km s\(^{-1} \) and a high line ratio of Fe xxvi Lyα to Fe xxv Kα implying a plasma temperature of \( 1.3 \times 10^7 \) K. This high-velocity, hot plasma cannot be produced by stellar activity or the accretion inflow onto the SMBH. Our magnetohydrodynamical simulations show that, instead, it is naturally explained by a wind from the hot accretion flow, propagating out to \( \geq 10^6 \) times the gravitational radius of the SMBH. The kinetic energy and momentum of this wind can significantly affect the evolution of the circumnuclear environment and beyond.

Lying at a distance of \( \sim 3.6 \) Mpc and having a systemic velocity of \( \sim 34 \) km s\(^{-1} \) (ref. 13), the massive spiral galaxy M81 (or NGC 3031) harbours one of the nearest super-massive black holes (SMBHs), commonly known as M81*, with an estimated mass \( M_{\text{BH}} \approx 7 \times 10^9 \) M\(_{\odot} \) (ref. 14). The low bolometric luminosity compared with the Eddington luminosity (\( L_{\text{bol}}/L_{\text{Edd}} \approx 3 \times 10^{-5} \) (ref. 15)), the existence of a radio jet16 and the likely absence of a classical thin accretion disk17,18 together make M81* a prototype low-luminosity active galactic nucleus (LLAGN) powered by a hot accretion flow19.

The X-ray spectrum of M81* is dominated by a power-law continuum, but also exhibits a number of prominent emission lines, in particular, highly ionized iron lines including Fe xxv Kα and Fe xxvi Lyα20–23. These lines, typically produced in a hot plasma with temperatures of \( 10^7–10^8 \) K, hold promise for probing the accretion physics of LLAGNs. For this reason, M81* has been the target of the High Energy Transmission Grating (HETG) spectrometer onboard the Chandra Observatory in a total exposure of 430 ks (Extended Data Table 1 and Extended Data Fig. 1). These deep Chandra–HETG observations obtained high-quality X-ray spectra of M81* from within a projected radius of \( R_{\text{proj}} \approx 42 \) pc (equivalent to \( \sim 1.2 \times 10^7 \) \( r_g \)), where \( r_g \equiv GM_{\text{BH}}/c^2 \) is the gravitational radius of the black hole, \( G \) is the gravitational constant and \( c \) is the speed of light, providing a line-of-sight velocity resolution of 300–2,000 km s\(^{-1} \) over the photon energy range of 0.5–8 keV.

We perform a blind search of emission and absorption lines in the HETG spectra against a baseline continuum model (Methods and Extended Data Fig. 2). Determined from a joint fit of the HETG spectra covering 0.5–8 keV and of Nuclear Spectroscopic Telescope Array (NuSTAR) spectra covering 3–79 keV, this baseline model is a single power law with a photon index of 1.88 ± 0.01 (quoted errors are at 90% confidence level, unless otherwise stated), subject to Galactic foreground absorption towards M81. It is noteworthy that the spectra show no sign of a Compton hump, suggesting that reflection from a putative accretion disk is low or absent4. Although there is hint of a slight softening at the high-energy end of the NuSTAR spectra, our test using a power law with an exponential cut-off finds no significant effect in the baseline continuum below 8 keV. The blind search identifies a number of significant emission lines but no absorption lines. In particular, four emission lines are found at a most probable centroid energy of 6.40 keV, 6.69 keV, 6.90 keV and 7.05 keV, respectively (Fig. 1a), all having a significance of \( \geq 95\% \) and a false detection probability of \( <0.1\% \).

The four lines are further characterized by four Gaussians to simultaneously determine the line widths and fluxes (Table 1 and Fig. 1b). The 6.40 keV line, having an apparent line width of \( 45 \pm 3 \) eV, is consistent with the Fe xxv Kα triplet. The 6.90 keV line, the strongest among the four, was previously detected in an HETG spectrum of shallower exposure and was suggested to be a Fe xxvi Lyα line redshifted from the rest-frame energy of 6.966 keV, but the cause of the implied Doppler velocity (\( \sim 3000 \) km s\(^{-1} \)) was unclear21. The fourth and weakest line at 7.05 keV is unambiguously detected, but its interpretation is less straightforward. It is tempting to associate this line with Fe i Kβ, which has a rest-frame energy of 7.058 keV. However, the Kβ–to-Kα intensity ratio of neutral or very weakly ionized Fe has a canonical value of \( \sim 0.13 \) (ref. 23), whereas the observed intensity ratio between the 7.05 keV and 6.40 keV lines is 0.69 ± 0.39 (determined using a bootstrap method). Hence, the 7.05 keV cannot be solely accounted for by Fe i Kβ. A more plausible explanation for the 7.05 keV line is a blueshifted Fe xxvi Lyα line that pairs with the 6.90 keV line in a way that is roughly symmetric about the rest-frame energy. Such a line pair signifies bulk motions of a bipolar outflow or a rotating disk or ring.

We verify this scenario with a phenomenological spectral model, which consists of a pair of collisionally ionized, optically













lines...
thin plasma (APEC\textsuperscript{23} in Xspec), one accounting for the redshifted component and the other for the blueshifted component. The two apec components are required to have the same plasma temperature and metal abundance (fixed at solar\textsuperscript{17}) but exactly inverse line-of-sight velocities, and their normalizations are allowed to vary. A power law and two Gaussians are also included to account for the continuum and the putative Fe i Kα and Kβ lines (adopting a fixed Kβ-to-Kα ratio of 0.13). All these components are subject to the Galactic foreground absorption. This phenomenological model results in a good fit to the HETG spectrum over 5–8 keV and particularly to the putative Fe i lines (Fig. 1c and Table 2). The best-fit plasma temperature, $kT_p = 11^{+3}_{-1}$ keV (where $h$ refers to high temperature and $k$ is the Boltzmann constant), is mainly driven by the relative strength between Fe xxvi Ly\textalpha and Fe xxv Kα and signifies an exceptionally hot plasma compared to virial temperature, $kT_v = GM(<R_{max})/M_{max} \approx 0.1$ keV (where $\mu \approx 0.6$ is the mean molecular weight and $m_p$ is the mass of proton). The best-fit absolute line-of-sight velocity, $2.8^{+0.5}_{-0.6} \times 10^5$ km s\textsuperscript{-1}, is consistent with the interpretation of the 6.90/7.05 keV lines as symmetrically redshifted/blueshifted Fe xxvi lines. (The same Doppler shift that should be akin to Fe xxv Kα is less appreciable, owing to

**Fig. 1 | Detection and characterization of highly ionized Fe lines.** a, Blind line search of the HEG first-order spectrum identifies four significant Fe lines. Blue, green and orange contours indicate the confidence levels of 99%, 90% and 68% of a test line, respectively, according to the differential Cash statistic (C-stat) value $\Delta C$ against the baseline continuum model. Black contour denotes where $\Delta C = +0.5$. The ‘+’ sign marks the most probable centroid energy and normalization for each line. b–d, The HEG first-order spectrum (black crosses), binned to achieve a signal-to-noise ratio greater than 3 for illustration. Error bars represent 1σ. The purple solid line indicates the total model. The residual-to-error ratio $\chi$ is shown at the bottom of each panel. In b, each of the four Fe lines is fitted by a Gaussian profile (green dotted line), top of the baseline power-law model (purple dotted line). In c, the model consists of a power law (purple dotted line), two Gaussians that account for the neutral Fe Kα (6.40 keV) and Kβ (7.058 keV) lines (green dotted line) and two apec components with a line-of-sight velocity of $\pm 2,800$ km s\textsuperscript{-1} (blue and orange dashed lines). In d, the two apec components are replaced by a synthetic wind spectrum (black dashed line) with a viewing angle of 15°.

Table 1 | Detection of the Fe lines

| $E_0$ (keV) | Significance | $E_\gamma$ (keV) | $\sigma_\gamma$ (eV) | $F$ (erg s\textsuperscript{-1} cm\textsuperscript{-2}) | EW (eV) |
|-----------|-------------|---------------|----------------|----------------|---------|
| 6.395     | $>99.99\%$  | $6.397^{+0.002}_{-0.008}$ | 5\textsuperscript{+2}_{-1} $\times 10^{-14}$ | 43.4 $\pm$ 0.4 |
| 6.688     | 99.86\%     | $6.666^{+0.003}_{-0.005}$ | 4\textsuperscript{+3}_{-2} $\times 10^{-14}$ | 57.4 $\pm$ 0.9 |
| 6.902     | $>99.99\%$  | $6.914^{+0.022}_{-0.021}$ | 3\textsuperscript{+2}_{-1} $\times 10^{-14}$ | 80.8 $\pm$ 0.4 |
| 7.050     | 94.76\%     | $7.046^{+0.006}_{-0.005}$ | 2\textsuperscript{+3}_{-2} $\times 10^{-14}$ | 31.2 $\pm$ 0.7 |

$E_0$, most probable line energy determined from blind line search; $E_\gamma$, line centroid energy; $\sigma_\gamma$, width; $F$, flux; EW, equivalent width from a Gaussian model. Errors are at the 90% confidence level; upper limits in the line width are given at the 3σ level.
the intrinsic width of the triplet.) The redshifted and blueshifted components have a flux ratio of $1.6^{+0.2}_{-0.2}$.

Additional emission lines are found in the HETG spectrum at lower energies, in particular between 1 keV and 3 keV (Extended Data Fig. 3 and Extended Data Table 2), which are mainly identified as the helium-like and hydrogen-like transitions of α elements (Si, S, and Ar). The pair of 11 keV apec components, however, cannot simultaneously account for these low-energy lines, as most low-Z elements would become fully ionized at this high temperature. Moreover, despite a higher velocity resolution at these low-energy lines, none of them show a line broadening or Doppler shift comparable to that of Fe xxvi Lyα, indicating that the line-of-sight velocity of ±2,800 km s$^{-1}$ is related only to the 11 keV plasma. Hence, we introduce a third apec component to account for the He-like and H-like lines of low-Z elements. It is also necessary to introduce two additional Gaussian components to account for the neutral Kr line of Si and Ar. This multi-component model leads to a reasonably good fit to the HETG spectrum over the 0.5–8 keV range (Table 2), in which the third apec component has a temperature of $kT_3 = 0.9^{+0.1}_{-0.1}$ keV (where 1 refers to low temperature) and an unabsorbed 0.5–10 keV luminosity of $3.3(\pm0.5) \times 10^{39}$ erg s$^{-1}$. This 0.9 keV plasma is unseen in the HETG zeroth-order spectrum of an annular region immediately outside $R_{max}$ (Methods and Extended Data Fig. 4), suggesting that it is spatially confined and may trace a circumnuclear diffuse hot gas.

The high-velocity Fe lines can in principle be produced in stellar activities such as young supernova remnants or massive star binaries with strong colliding winds. However, the X-ray luminosity of the 11 keV plasma, $3.8 \times 10^{39}$ erg s$^{-1}$, is exceedingly high for a supernova remnant; only supernovae younger than $\sim10^4$ days can have X-ray luminosities $\gtrsim10^{39}$ erg s$^{-1}$ (ref. 25), and such a recent and nearby supernova could hardly have been missed by astronomers25, consistent with our estimated supernova birth rate of $\lesssim5 \times 10^{-5}$ yr$^{-1}$ within $R_{max}$. Similarly, the observed X-ray luminosity and plasma temperature are too high for a colliding wind binary26. Unresolved X-ray binaries are also insufficient to account for the observed X-ray flux, given the moderate amount of stellar mass and star formation rate within $R_{max}$ (Methods). Therefore, we conclude that stellar activities cannot be responsible for the high-velocity 11 keV plasma. Photoionization by the LLAGN can be safely ruled out as...
the cause of the highly ionized Fe lines, because the required irradiating luminosity is orders of magnitude higher than the observed X-ray luminosity of M81* (Methods and Extended Data Fig. 5). The high-velocity 11 keV plasma is also highly unlikely to be a jet-driven outflow, because a jet can only drive a fast outflow by a shock ahead of the ‘jet head’, leaving little effect on the kinetics of the gas behind27. The steady jet of M81* should have long passed the region (~42 pc) probed by the HETG observations.

Another possibility is that the highly ionized Fe lines may be produced in the accretion inflow, which, for an LLAGN such as M81*, consists of a truncated thin disk plus an inner hot accretion flow28. The synthetic spectrum exhibits a double-peak Fe xxvi feature (see illustration in Fig. 2a). In the thin disk, the rotational velocity $V_{\text{rot}} \approx \sqrt{GM_\odot} / r$ can reach $\gtrsim 3,000$ km s$^{-1}$ at radii $r \lesssim 10^4 r_g$. Although this is compatible with the estimated truncated radius of $r_g \approx 10^4 r_g$, the disk temperature can reach only $\lesssim 10^6$ K, which is too low to be consistent with the observed line ratio of Fe xxvi to Fe xxv. Inside $r_\text{tr}$, the thin disk is replaced by a geometrically thick hot inflow, where plasma temperatures become much higher ($\approx 10^9 (2 \times 10^4 r_g / r)^2$ K). In this case, our numerical simulation of the hot accretion flow in M81* predicts an equivalent width of Fe xxvi Ly$\alpha$ that is much lower than the observed value ($\approx 110$ eV), because the temperature of the accretion flow is so high that the plasma is too strongly ionized (Methods and Extended Data Fig. 6).

A larger $r_\text{tr}$ would in principle lead to stronger Fe xxvi Ly$\alpha$, however, the correspondingly decreased rotational velocity would result in a reduced Doppler shift inconsistent with the observed double-peak line profile. Therefore, the possibility that the high-velocity Fe lines originate in the accretion inflow, either the truncated thin disk or the inner hot accretion flow, can be ruled out.

This leaves a bipolar wind launched from the hot accretion flow as the most plausible origin of the high-velocity Fe lines. Such a wind, schematically illustrated in Fig. 2a, is a robust prediction by theory4 and numerical simulations of hot accretion flows1–4. Different from a relativistic jet, the wind originates from a large range of radius in the accretion flow, having a much wider opening angle and much smaller radial velocity. The temperature of the wind decreases from that of the hot accretion flow owing to adiabatic expansion when propagating outward, and thus may be suitable for producing the observed Fe lines.

We performed 2.5-dimensional (2.5D) magnetohydrodynamical (MHD) simulations of the wind launched from the hot accretion flow in M81* with $r_g = 3,000 r_g$ to obtain the spatial distributions of density, temperature, velocity and magnetic field (Fig. 2b–d), which in turn allow us to generate a synthetic X-ray spectrum to compare with the HETG spectrum (Methods). We find that self-absorption in the Fe xxvi Ly$\alpha$ and Fe xxv K$\alpha$ lines is negligible for the wind, which has an equivalent column density of $\lesssim 10^{24}$ cm$^{-2}$. A free parameter in this synthetic spectrum is the inclination angle between the jet axis and the line of sight. Figure 1d illustrates a synthetic spectrum with an inclination angle of $15^\circ$, a value consistent with that inferred from the plane of motion of circumnuclear warm gas29, and also compatible with the upper limit of $56^\circ$ inferred from radio observations of moving jet knots30. The synthetic spectrum exhibits a double-peak Fe xxvi Ly$\alpha$ profile and a high xxvi- to-xxv flux ratio, both in reasonable agreement with the observed spectrum. The redshifted and blueshifted components in the synthetic spectrum have nearly equal amplitudes, which is a consequence of the mirror symmetry about the equatorial plane of the accretion flow assumed in our simulation. In reality, the wind is usually intrinsically asymmetric above and below the equatorial plane, easily causing mild (at a level of $\approx 25\%$) inequality in the gas density and hence the $\approx 60\%$ difference between the observed redshifted/blueshifted components on timescales significantly shorter than the wind dynamical time of $10^4 r_g / r_\text{tr} \approx 10$ yr, with $10^4 r_g$ being the region where most of the Fe xxvi line emission originates and $r_\text{tr}$ being the wind radial velocity. It is noteworthy that the moderate inequality between the blueshifted and redshifted Fe lines does not affect our arguments and conclusions against the aforementioned alternative origins of a high-velocity hot plasma.

Theoretically, the outflow rate of the hot wind should be nearly equal to the inflow rate of the hot accretion flow (also of the truncated thin disk) at $r_\text{tr}$. The outflow rate can be estimated using the density and radial velocity information from the wind simulation, and is found to be $\approx 2 \times 10^{-3} M_\odot$ yr$^{-1}$. Indeed, this value is in good agreement with the estimated mass inflow rate $(4 \times 10^{-3} M_\odot$ yr$^{-1})$ of the warm ionized gas at a radius of $20$ pc ($\approx 6 \times 10^4 r_g$), lending strong support to the wind model. The associated wind kinetic power is $\approx 2 \times 10^{40}$ erg s$^{-1}$, equivalent to 10% of the bolometric luminosity of M81* (ref. 31). By contrast, the wind momentum flux, $\approx 6 \times 10^{19}$ g cm s$^{-2}$, is three times the photon momentum flux $(L_{\text{bol}} / c \approx 2 \times 10^{41}$ g cm s$^{-2}$).

### Table 2: Broad-band spectral fit results

| Data and model | $C / \text{d.f.}$ | $I'$ | $N_{\text{pl}}$ | $kT_p$ | $V_p$ | $N_{\text{MeG}}$ | $N_{\text{HeG}}$ | $kT_l$ | $N_l$ | $N_{\text{wind}}$ |
|---------------|-----------------|-----|--------------|--------|------|----------------|----------------|--------|------|----------------|
| PL            | HEG (1-6/75–8 keV) | 4,388/4,142 | 1.88 $^{+0.03}_{-0.02}$ | 3.42 $^{+0.03}_{-0.02}$ | -    | -              | -              | -      | -    | -              |
|               | MEG (0.5–5 keV)  | 4,586/4,557 | 3.55 $^{+0.02}_{-0.02}$ | -      | -    | -              | -              | -      | -    | -              |
|               | FPMA (3-6/75–79 keV) | 3,770/3,452 | 6.73 $^{+0.09}_{-0.09}$ | -      | -    | -              | -              | -      | -    | -              |
|               | FPMB (3-6/75–79 keV) | 3,546/3,456 | 6.87 $^{+0.09}_{-0.09}$ | -      | -    | -              | -              | -      | -    | -              |
|               | PL + apec, x 2   |                 |                 | -      | -    | -              | -              | -      | -    | -              |
|               | HEG (5–8 keV)    | 408/363 | 1.88  | 3.02 $^{+0.10}_{-0.09}$ | 11 $^{+3}_{-2}$ | 2.8 $^{+0.2}_{-0.1}$ | 10 $^{+5}_{-4}$ | 5 $^{+4}_{-3}$ | 0.9 $^{+0.1}_{-0.1}$ | 11 $^{+0.2}_{-0.2}$ |
|               | PL + wind        |                 |                 | -      | -    | -              | -              | -      | -    | -              |
|               | HEG (5–8 keV)    | 418/365 | 1.88  | 2.07  | -    | -              | -              | -      | -    | 0.6            |
|               | PL + apec, x 2 + apec |         |                 | -      | -    | -              | -              | -      | -    | -              |
|               | HEG (1–8 keV)    | 4,541/4,302 | 1.88  | 2.94 $^{+0.14}_{-0.09}$ | 16 $^{+7}_{-6}$ | 2.9 $^{+0.2}_{-0.1}$ | 10 $^{+5}_{-4}$ | 5 $^{+4}_{-3}$ | 0.9 $^{+0.1}_{-0.1}$ | 11 $^{+0.2}_{-0.2}$ |
|               | MEG (0.5–5 keV)  | 4,498/4,551 | 1.88  | -      | -    | -              | -              | -      | -    | -              |

The first column shows the fitted spectral set (with the energy band in parentheses) and the adopted model. FpMA(B), focal plane module A(B); HeG, high-energy grating; MeG, medium-energy grating; PL, power law; C, Cash statistic; $I'$, photon index of the power law; $N_{\text{pl}}$, normalization of the power-law component; $kT_p$, plasma temperature, in units of keV, which is the same for the two apec, components; $V_p$, absolute line-of-sight velocity of the two apec, components, in units of $10^5$ km s$^{-1}$; $N_{\text{MeG}}$, normalization of the power-law component with a viewing angle of 15°, in units of $10^{42}$ cm$^{-2}$; $N_{\text{HeG}}$, normalization of the hot wind model with a viewing angle of $15^\circ$, in units of $10^{42}$ cm$^{-2}$. Quoted errors are at 90% confidence level.
The bulk of the wind momentum and kinetic energy should be deposited into the interstellar medium (ISM) owing to the wide opening angle of the wind, thereby providing an effective feedback to the host galaxy and regulating the growth of the SMBH. This is supported by the existence of the 0.9 keV component in the X-ray spectrum, which is likely the result of the outward propagating wind shock-heating the ISM. Numerical simulations of wind–ISM interaction in a realistic galactic environment find that winds with a similar power from a hot accretion flow stop roughly at a few times $10^5 r_g$, which is consistent with the extent of the 0.9 keV gas. The internal energy of this 0.9 keV gas, estimated to be $\lesssim 1.2\times 10^{49}$ erg, can be converted from the wind kinetic energy in $2\times 10^5$ yr, comparable to the dynamical time of the wind. Such a wind–ISM interaction is also evidenced by a previously identified blob of warm ionized gas located $\sim 10$ pc south of M81* (ref. 8).

### Methods

**X-ray data.** In this study we used two sets of X-ray data: Chandra Advanced CCD Imaging Spectrometer (ACIS) and HETG first-order grating spectra to resolve emission lines at a velocity resolution of $300-2000$ km s$^{-1}$ and over an energy range of 0.5–8 keV, and NuSTAR spectra to constrain the continuum over 3–79 keV. A log of the X-ray data is given in Extended Data Table 1.

Chandra observed M81* with the combined operation of its ACIS and HETG in 15 epochs between 24 February 2005 and 12 August 2006. The publicly available data were preprocessed using CIAO v4.1 and calibration files (CALDB v4.8.2) and by following the standard pipeline. Time intervals of high particle background were filtered, resulting in a total cleaned exposure of 429.2 ks. The first-order spectra of both the high-energy grating (HEG) and medium-energy grating (MEG) were extracted for each observation, using the CIAO tools xresolve_events and xtotals. For the source spectra, we adopted the default cross-dispersion half-width of 2.4″ (equivalent to a projected radius $R_{\text{proj}} \approx 42$ pc), which ensures the same enclosed energy fraction ($\approx 97$%) for different wavelengths, according to the Proposer’s Observatory Guide (https://cxc.cfa.harvard.edu/proposer/POG/).

We also tested a smaller cross-dispersion half-width of 1.5″ and found that the main spectral properties, in particular the Fe lines, are unaffected. The background spectra were extracted from a default adjacent region of 19.1″ full width half above and below the source region. As shown in Extended Data Fig. 1, the first-order arms have a varied position angle among the 15 observations, and in some instances intercede off-nuclear point sources (mostly X-ray binaries belonging to M81 (ref. 8)). Hence, we carefully examined each observation to mask out any contaminating sources. We then co-added the spectra of grist-first-order and of individual observations to form a combined HEG–MEG spectrum, along with the exposure-weighted ancillary response files and redistribution matrix files. The corresponding background spectra were similarly co-added. Thanks to the relatively high flux of M81*, the background contributes less than 2% to the source spectrum. NuSTAR observed M81* between 18 May 2015 and 20 May 2015, corresponding to a duration of 342 ks. Data reduction was performed using NuSTARDAS v1.7.1 and the HEASOFT/FPFOOLS v6.21.1. After applying pipeline to obtain cleaned event files with a net exposure of 690.9 ks, we extracted the spectrum of M81* over 3–79 keV from both focal plane modules A and B (FPMA and FPMB). The source region was defined as a circle with a radius of 100″, approximately enclosing 90% of the counts from a point source, whereas the background was extracted from an annulus with an inner radius of 105″ and an outer radius of 175″ (Extended Data Fig. 1). We note that the NuSTAR spectral extraction region encloses 61 off-nuclear X-ray sources as detected by Chandra*. Their collective 0.5–10 keV flux is less than 2% of the flux of M81* in the same energy range. Therefore, the contribution of these off-nuclear sources is expected to be negligible in the NuSTAR spectra.

**Baseline continuum model.** Spectral fitting was carried out with Xspec v12.9.1, which employs ATOMDB v3.0.9 (http://www.atomdb.org/) for the modelling of atomic lines. To preserve the maximally possible spectral resolution, we grouped the co-added spectra to have at least one count per bin and employed the Cash statistic ($C$-stat) in the fit.

Previous studies have shown that the X-ray spectrum of M81* is dominated by a single power law$^{18-21}$, likely arising from a synchrotron jet and/or Comptonization in the hot accretion flow. Hence, an absorbed power law ($\text{tbabs}\times\text{powerlaw}$) is adopted as the baseline continuum. The Chandra–HETG spectra over 0.5–8 keV and the NuSTAR spectra over 3–79 keV were jointly fitted to provide the tightest constraint on the photon index (Table 2 and Extended Data Fig. 2). The normalization was allowed to vary, accounting for the different enclosed energy fractions and possible flux variability between the Chandra and NuSTAR spectra. The absorption column density ($N_H$) is tied among the spectra and the absorption continua are constrained to a minimum value of $3\times 10^{20}$ cm$^{-2}$ to be consistent with the cosmic-ray emission from unresolved X-ray binaries plus the point-spread-function-scattered photons from M81*. Although an additional thermal component is not formally required...
by the spectrum, we added an apoc model to the fit, fixing the plasma temperature at 0.9 keV and the abundance at solar. The normalization was adjusted to obtain the 3σ upper limit allowed by the spectrum. This corresponds to an unabsorbed 0.5–10 keV luminosity of 2.2 × 10^{37} erg s^{-1}, which is about an order of magnitude lower than that of the 0.9 keV component found in the first-order spectrum (and a factor of at least 40 lower in surface brightness), suggesting that the latter is spatially confined and traces a circumnuclear hot gas.

Black hole mass, enclosed stellar mass and star formation rate. The mass of the SMBH in M81 has been estimated in several studies. Based on the kinematics of circumnuclear (≤10 pc) ionized gas measured by the Space Telescope Imaging Spectrograph of the Hubble Space Telescope, Devereux et al.25 obtained M_{BH} = 7.7 × 10^{6} M_{⊙} along with an inclination angle of i = 14° for the plane of gas motion. A value of M_{BH} = 6.4(20%) × 10^{6} M_{⊙} was reported by ref. 27 based on stellar motions and redshifts of background stars. Schöller Muller et al.28 obtained M_{BH} = 5.8(6.3) × 10^{6} M_{⊙} (rescaled to our adopted distance of 3.6 Mpc) based on the relation between black hole mass and stellar velocity dispersion (σ_{stellar}) (ref. 27). We adopted M_{BH} = 7.0 × 10^{6} M_{⊙} as our fiducial black hole mass.

The stellar mass projected within R_{200} was estimated to be M_{*} = 3 × 10^{10} M_{⊙} based on the empirical relation of ref. 15, which is about an order of magnitude larger than that of the 0.9 keV component found in the first-order spectrum (and a factor of at least 40 lower in surface brightness), suggesting that the latter is spatially confined and traces a circumnuclear hot gas.
in the latitudinal direction extended from θ = 5° to 50°. The rotation axis was avoided given the singularity of spherical coordinate and the existence of the jet; the equatorial plane was avoided because the wind occupies only this region when it propagates outward from the hot accretion flow, according to ref. 2. (refer to Fig. 1 therein). In fact, our current simulation again confirms this result. We also neglected the jet, because the existence of the jet does not affect the dynamics of the wind and the jet does not produce emission lines. At the inner radial boundary we injected the wind following the aforementioned inner boundary conditions. As usual, the outflow boundary condition was adopted at η∞, the axiymmetric boundary condition was adopted at θ = 5° and the reflecting boundary condition was adopted at θ = 50°.

The two-dimensional distributions of temperature and density of the simulated wind are shown in Fig. 2a–c, overlapped with the velocity vector. The two-dimensional grid was then expanded into a three-dimensional grid by assuming axiisymmetry about the jet axis and mirror symmetry about the equatorial plane. We were then in a position to predict the wind X-ray spectrum. To do so, we first calculated the density-weighted thermal emission for each grid in the black hole rest frame, again using ATOMDB and assuming solar abundance. The synthetic spectrum was then produced by integrating along a given viewing angle. The Doppler effect was included according to the projected velocity in each grid. The gravitational lensing effect was also taken into account, which slightly boosts the redshifted component (that is, from behind the SMBH in the case of an outflow) and partially compensates for the Doppler dimming effect. The absolute normalization of the gas density was determined by matching the integrated spectrum to the observed spectrum (Fig. 1). We verified that self-absorption in the Fe xxvi Lyα spectrum to the observed spectrum (Fig. 1d). We verified that self-absorption in the Fe xxvi Lyα spectrum to the observed spectrum (Fig. 1d).

Data availability
Source data are provided with this paper. The original X-ray data used in this work are publicly available in the online HEASARC archive at https://heasarc.gsfc.nasa.gov/cgi-bin/w3Browse/w3Browse.pl. Reduced X-ray spectra are available in Supplementary Data 1–5.

Code availability
Spectral analysis is conducted using Xspec (https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/), which employs ATOMDB for the modelling of atomic lines. The ZEUS-MP2 and ATHENA++ codes used in this work are publicly available at https://github.com/bowshee/ZEUS-MP_2 and at https://github.com/Princeton/university/athena-public-version. The wind simulation data for Fig. 2 are provided with this paper.

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Author contributions
This research programme was designed and framed by Z.L. and F.Y. Analysis and modelling of the X-ray data were performed by F.S. with the help of Z.L. Numerical simulations of the accretion flow and wind were performed by B.Z. and F.Y. All authors were involved in the discussion and interpretation of the results presented, and all contributed to writing the paper.

Competing interests
The authors declare no competing interests.

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Extended Data Fig. 1 | The combined Chandra/HETG images highlighting the 1st-order MEG/HEG arms. Spectra are extracted from the individual observations of different roll angles and then combined to form the final spectrum. The green rectangles illustrate the spectral extraction region (solid rectangles for the source and the adjacent dashed rectangles for the background) for one of the 15 observations. The NuSTAR source region is marked by the vermilion solid circle, while the corresponding background region is marked by the vermilion dashed annulus. Discrete sources falling within the NuSTAR spectral extraction regions are not excluded, but their collective flux contribution is negligible.
Extended Data Fig. 2 | Observed X-ray spectra of M81*. Red: coadded Chandra/MEG 1st-order spectrum; Black: coadded Chandra/HEG 1st-order spectrum; Green: NuSTAR/FPMA spectrum; Blue: NuSTAR/FPMB spectrum. The error bars are of 1σ. The best-fit absorbed power-law model is shown by the solid lines. The ratio of residual/error is shown in the bottom panel. Significant excess is seen between 6–7 keV due to the presence of Fe lines. The spectra shown here are binned to achieve a S/N greater than 3 for better illustration, while in the actual spectral fit throughout this work the spectra are binned to have at least one count per bin to optimize the spectral resolution.
Extended Data Fig. 3 | Blind line search of the MEG and HEG spectra over 1–3 keV. Blue, green and orange contours indicate confidence level of 99%, 90% and 68%, respectively, of a test line according to the differential $C$-stat value against the baseline continuum model. The black contour denotes where $\Delta C = +0.5$. Significant lines with an identified atomic transition are denoted with the pink vertical dashed lines.
Extended Data Fig. 4 | Coadded HETG zeroth-order spectrum from an annulus of inner-to-outer radii of 2.5″ -5.0″ around M81*. The spectrum can be well fitted by an absorbed power-law, shown as the magenta line. The error bars are of 1σ. The ratio of residual/error is shown in the bottom panel. An additional thermal component, represented by an apec model with a plasma temperature of 0.9 keV, is allowed by the data and shown as the blue line. The sum of the power-law and apec is plotted as the black line.
Extended Data Fig. 5 | Predicted Fe line luminosity of an isotropic and uniform gas cloud photonized by a central AGN. The upper (lower) panel is for Fe XXVI Lyα (XXV Kα). The ionization parameter is evaluated for an intrinsic X-ray spectrum same as M81* and over photon energy of 2-10 keV. The cloud has an equivalent hydrogen column density of $N_H = 10^{21}$ cm$^{-2}$ (black solid line), $10^{22}$ cm$^{-2}$ (red dash-dotted line) and $10^{23}$ cm$^{-2}$ (blue dashed line). The black dotted horizontal line in each panel marks the observed line luminosity, which is substantially higher than the predicted values.
Extended Data Fig. 6 | Predicted 6.5–7.3 keV spectrum from simulation of the hot accretion flow. The viewing angle is set to be 45° with respect to the jet axis. The blue, red and black curves show the blueshifted, redshifted and total spectrum, respectively. The spectra have been convolved with the HEG instrumental response. The black crosses mark the observed spectrum as a reference. The error bars are of 1σ. The observed Fe XXVI and XXV lines have an equivalent width substantially higher than predicted by the hot accretion flow.
Extended Data Table 1 | Log of X-ray observations

| Observatory | ObsID | Start Time (UT) | Exposure (ks) |
|-------------|-------|-----------------|---------------|
| Chandra     | 6174  | 2005-02-24T06:56| 44.61         |
| Chandra     | 6346  | 2005-07-14T01:44| 54.48         |
| Chandra     | 6347  | 2005-07-14 19:25| 63.87         |
| Chandra     | 5601  | 2005-07-19 14:26| 83.07         |
| Chandra     | 5600  | 2005-08-14 09:51| 35.96         |
| Chandra     | 6892  | 2006-02-08 20:21| 14.76         |
| Chandra     | 6893  | 2006-03-05 23:42| 14.76         |
| Chandra     | 6894  | 2006-04-01 10:38| 14.76         |
| Chandra     | 6895  | 2006-04-24 08:18| 14.56         |
| Chandra     | 6896  | 2006-05-14 13:01| 14.76         |
| Chandra     | 6897  | 2006-06-09 18:14| 14.76         |
| Chandra     | 6898  | 2006-06-28 23:36| 14.75         |
| Chandra     | 6899  | 2006-07-13 13:41| 14.94         |
| Chandra     | 6900  | 2006-07-28 11:10| 14.41         |
| Chandra     | 6901  | 2006-08-12 16:15| 14.76         |
| NuSTAR      | 60101049002 | 2015-05-18 19:31 | 223.4         |
Extended Data Table 2 | Additional Emission lines in the HETG spectrum

| Line    | $E_0$ | Significance | $E_c$ | $\sigma_c$ | Flux | EW |
|---------|-------|--------------|-------|------------|------|----|
| Ne X Ly$\alpha$ | 1.022 | >99.99% | 1.022$^{+0.002}_{-0.001}$ | 3$^{+2}_{-1}$ | 2.7$^{+1.0}_{-0.9}$ | 5.67$^{+0.04}_{-0.02}$ |
| Mg XII Ly$\alpha$ | 1.473 | 99.87% | 1.474$^{+0.001}_{-0.003}$ | 3$^{+3}_{-1}$ | 1.1$^{+0.5}_{-0.4}$ | 2.91$^{+0.02}_{-0.03}$ |
| Si I K$\alpha$ | 1.740 | 99.81% | 1.739$^{+0.001}_{-0.001}$ | <13 | 0.5$^{+0.3}_{-0.2}$ | 1.58$^{+0.03}_{-0.03}$ |
| Si XIII K$\alpha$ (f) | 1.839 | 82% | 1.840$^{+0.006}_{-0.006}$ | - | <1.0 | <1.6 |
| Si XIII K$\alpha$ (r) | 1.865 | 99.50% | 1.865$^{+0.002}_{-0.004}$ | 4$^{+3}_{-2}$ | 1.1$^{+0.6}_{-0.5}$ | 3.38$^{+0.02}_{-0.03}$ |
| S XV K$\alpha$ (f) | 2.430 | 99.04% | 2.415$^{+0.008}_{-0.008}$ | <30 | 1.3$^{+0.8}_{-0.7}$ | 3.58$^{+0.07}_{-0.05}$ |
| S XV K$\alpha$ (r) | 2.461 | 99.72% | 2.447$^{+0.009}_{-0.009}$ | <22 | 1.2$^{+0.8}_{-0.7}$ | 3.45$^{+0.06}_{-0.05}$ |
| S XVI Ly$\alpha$ | 2.622 | 98.26% | 2.621$^{+0.010}_{-0.010}$ | <15 | 1.2$^{+1.0}_{-0.8}$ | 3.47$^{+0.02}_{-0.14}$ |
| Ar I K$\alpha$ | 2.957 | 99.98% | 2.958$^{+0.003}_{-0.003}$ | <25 | 1.5$^{+0.8}_{-0.7}$ | 4.72$^{+0.08}_{-0.05}$ |

(1) Each identified transition is followed by two rows, the upper row for the HEG measurement and the lower row for the MEG measurement. (2) Rest-frame energy of the identified transition, in units of keV. (3) Significance of the line. (4) The best-fit central energy in units of keV. (5) The Gaussian line width, in units of eV. 3σ upper limit is provided for unresolved lines. (6) Line flux in units of $10^{-14}\text{erg cm}^{-2}\text{s}^{-1}$. 3σ upper limit is provided for undetected lines. (7) Equivalent width in units of eV. Quoted errors are at 90% confidence level.