There are two proposed explanations for ultraluminous X-ray sources\(^2,3\) (ULXs) with luminosities in excess of \(10^{39}\) erg s\(^{-1}\). They could be intermediate-mass black holes (more than 100–1,000 solar masses, \(M_\odot\)) radiating at sub-maximal (sub-Eddington) rates, as in Galactic black-hole X-ray binaries but with larger, cooler accretion disks\(^4,5\). Alternatively, they could be stellar-mass black holes radiating at Eddington or super-Eddington rates\(^2,6\). On its discovery, M 101 ULX-1\(^4,7\) had a luminosity of \(3 \times 10^{39}\) erg s\(^{-1}\) and a supersoft thermal disk spectrum with an exceptionally low temperature—uncomplicated by photons energized by a corona of hot electrons—more consistent with the expected appearance of an accreting intermediate-mass black hole\(^4,8\). Here we report optical spectroscopic monitoring of M 101 ULX-1. We confirm the previous suggestion\(^8\) that the system contains a Wolf-Rayet star, and reveal that the orbital period is 8.2 days. The black hole has a minimum mass of \(5M_\odot\), and more probably a mass of \(20M_\odot - 30M_\odot\), but we argue that it is very unlikely to be an intermediate-mass black hole. Therefore, its exceptionally soft spectra at high Eddington ratios violate the expectations for accretion onto stellar-mass black holes\(^9,10\). Accretion must occur from captured stellar wind, which has hitherto been thought to be so inefficient that it could not power an ultraluminous source\(^11,12\).

Although it is desirable to obtain the primary mass of a ULX through measuring the motion of its companion (the secondary), this is only possible in the X-ray-low state (that is, at low X-ray luminosities) because the X-ray irradiated accretion disk will dominate optical emission in the X-ray-high state\(^14,15\). We performed a spectroscopic monitoring of M 101 ULX-1, and present broad emission lines with FWHM up to 20 Å, including strong He\(^\text{II}\) 4,686 Å, He\(^\text{I}\) 5,876 Å and He\(^\text{II}\) 6,679 Å lines, weaker He\(^\text{I}\) 4,471 Å, He\(^\text{I}\) 4,922 Å and He\(^\text{II}\) 5,411 Å lines and N\(^\text{III}\) 4,640 Å lines. The observed He\(^\text{I}\) 5,876/He\(^\text{II}\) 5,411 Å equivalent width ratio suggests a Wolf-Rayet star of WN8 sub-type, consistent with the absence of carbon emission lines for WC stars (such as C\(^\text{III}\) 5,696 Å and C\(^\text{IV}\) 5,812 Å). The intensities of the helium emission lines can be best reproduced by an atmospheric model\(^16\) of a Wolf-Rayet star with \(R_\ast = 10.7R_\odot\), \(M_\ast = 17.5M_\odot\), \(L_\ast = 5.4 \times 10^5L_\odot\), \(T_\ast = 48\,400\,\text{K}\), \(M_\text{up} = 2 \pm 0.5 \times 10^{-3}\,M_\odot\,\text{yr}^{-1}\) and \(v_\text{esc} = 1,300 \pm 100\,\text{km s}^{-1}\) (with 68.3% uncertainties for the two continuously variable parameters; details of all parameters are given in Methods), consistent with those for a WN8 star. The mass–luminosity relation\(^17,18\) for Wolf-Rayet stars gives a more reliable mass estimate of \(19M_\odot\), which we use in the main text, with an estimated formal error of \(1M_\odot\).
campaign for M 101 ULX-1 from February to May 2010 during its expected X-ray-low states. The optical spectrum (Fig. 1) is characterized by broad helium emission lines, including the He II 4,686 Å line. Given the absence of broad hydrogen emission lines, which are detected in some ULXs from their X-ray irradiated accretion disk at very high luminosities, the donor cannot be hydrogen rich, and thus must be a Wolf-Rayet star or a helium white dwarf. The latter can be excluded because a white dwarf is roughly a million times dimmer than the observed optical counterpart even during the low states. Indeed, the optical spectrum is unique to Wolf-Rayet stars, and the intensities of the helium optical counterpart even during the low states. Indeed, the optical spectrum even during the low states. The probability of discovering a pole-on binary with $i < 3^\circ$ ($i = 5^\circ$) by mere chance is lower than 0.1% (0.3%). This makes it very unlikely that this system contains an IMBH of $1,000M_\odot$ ($300M_\odot$). If the peak luminosity of M 101 ULX-1 corresponds to less than 30% of the Eddington level—which is commonly assumed to be required to produce the thermally dominated spectral state—then the black-hole mass would exceed $50M_\odot$–$80M_\odot$. The true black-hole mass seems likely to be $20M_\odot$–$30M_\odot$ (see Methods for details).

The confirmation of a Wolf-Rayet star in the system, independent of the dynamical mass measurement, also suggests that M 101 ULX-1 is unlikely to be an IMBH. IMBHs cannot form directly through the collapse of massive stars, but it is suggested that they can form through mergers in dense stellar environments. However, any IMBH formed would not be seen as a ULX unless they capture a companion as a reservoir from which to accrete matter. Such a capture is a rare event even in dense stellar environments such as globular clusters or galactic bulges, to which M 101 ULX-1 apparently does not belong, and captures that can provide high-enough accretion rates to power a ULX are even more unusual. The rarity of Wolf-Rayet stars (there are about 2,000 such stars out of the 200 billion stars in a typical spiral galaxy like the Milky Way), it is extremely unlikely that M 101 ULX-1 is such a revived IMBH. Alternatively a huge population of IMBHs could somehow remain undetected, both with and without companions.

M 101 ULX-1 is thus a stellar black hole, although it is a member of the class of supersoft ULXs which have been considered to be outstanding IMBH candidates. Its combination of high luminosities and low disk temperatures (Fig. 3) strains our current understanding of accretion by stellar-mass black holes. Studies of Galactic black-hole X-ray binaries suggest that radiation at less than roughly 30% of the Eddington luminosity is dominated by the thermal emission from a hot disk ($\sim 1$ keV). A hard power-law component due to Comptonization by the disk corona becomes more and more significant when the luminosity increases to near-Eddington levels. When the luminosity increases further, to Eddington or super-Eddington levels, the Comptonized component begins to dominate the disk component, as observed for ULXs in the ultraluminous state. For example, the ultraluminous microquasar in M31 with a stellar-mass black hole ($\sim 10M_\odot$) and a luminosity of $10^{39}$ erg s$^{-1}$ exhibited hard X-ray spectra. If it were the same phenomenon, a hard X-ray spectrum would be expected for a stellar-mass black hole in M 101 ULX-1, whether it is radiating at sub-, near- or super-Eddington luminosities. The observed supersoft X-ray spectra lack hard photons above 1.5 keV, and can be described purely by cool accretion disks, uncomplicated by Comptonization, with exceptionally low temperatures of 90–180 eV (refs 4, 7). Including extra photoelectric absorption by the surrounding Wolf-Rayet wind in the spectral analysis would further lower the underlying disk temperatures and increase the luminosities, which would cause M 101 ULX-1 to deviate even farther from the expected hard spectra. This unambiguously demonstrates that stellar-mass black holes can have very cool accretion disks uncomplicated by the Comptonized component, contrary to standard expectations.

M 101 ULX-1 is the third known Wolf-Rayet/black-hole binary but is distinctly different from NGC 300 X-1 and IC 10 X-1. Whereas M 101 ULX-1 is a recurrent transient with supersoft spectra and low disk temperatures, both IC 10 X-1 and NGC 300 X-1 show constant X-ray output (despite apparent variations due to orbital modulation), hard spectra with a minor disk component, and disk temperatures above 1 keV (refs 19, 21, 29, Fig. 3). Hence the compact object in M 101 ULX-1 was considered to be an excellent IMBH candidate, whereas IC 10 X-1
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rates. However, M 101 ULX-1 demonstrates that this expectation is not always correct. In particular, transient outbursts of such wind-accreting system have generally not been included in theoretical ULX populations\textsuperscript{12,13}, but M 101 ULX-1 does attain ULX luminosities. Theorists have recently suggested that wind accretion may potentially also be significant for some progenitors of type Ia supernovae\textsuperscript{14}. M 101 ULX-1 empirically supports this reassessment of the potential importance of wind accretion.

METHODS SUMMARY

Analysis of earlier M 101 ULX-1 observations, data reduction and analysis of the Gemini/GMOS spectroscopic observations, determination of the Wolf-Rayet subclass and its physical parameters, the search for orbital periodicity, and determination of the properties of the Wolf-Rayet/black-hole binary are described in Methods.

Online Content Any additional Methods, Extended Data display items and Source Data are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Figure 3 The prototype ultraluminous supersoft X-ray source M 101 ULX-1 exhibits distinct spectral characteristics. M 101 ULX-1 is compared to Galactic black-hole X-ray binaries (GBHXRBs), Wolf-Rayet/black-hole binaries IC 10 X-1 and NGC 300 X-1, and other ULXs on the disk X-ray luminosity ($L_x$) versus disk temperature ($T_d$) plane, all plotted with the 68.3% uncertainties from the X-ray spectral fitting. Except for M 101 ULX-1, which can be fitted with a disk blackbody model with temperatures of 90–180 eV (refs 4, 7), all other X-ray sources are complicated by the presence of a hard power-law component due to Comptonization by a corona, and can be best fitted with a disk blackbody plus power-law composite model\textsuperscript{19}. Whereas GBHXRBs\textsuperscript{8} and the other two Wolf-Rayet/black-hole binaries\textsuperscript{9} with stellar black holes cluster in the same region, M 101 ULX-1 lies within a distinct region that has been expected to contain IMBH candidates, the same region as for some ULXs\textsuperscript{10}. The dotted lines describe the expected disk luminosity ($L_d$) for different disk temperatures for a fixed disk inner radius ($R_d$) based on the relation $L_d \propto R_d^2 T_d^4$. The two lines are offset by four orders of magnitude in luminosity, implying a factor of 100 differences in the disk inner radii, and a factor of 100 differences in the black-hole masses if the disk radius is tied to the innermost stable orbit of the black hole. Fitting ULX spectra with alternative Comptonization models can yield high disk temperatures consistent with those of stellar-mass black holes\textsuperscript{9}. However, the location of M 101 ULX-1 on the $L_x$–$T_d$ plane does not change because its spectra are not complicated by Comptonization.

and NGC 300 X-1 were expected to host stellar-mass black holes (as was later confirmed). The 8.2-day orbital period shows that M 101 ULX-1 is a wide binary, with components that would be separated by 50R\textsubscript{☉} for black-hole mass $M_\odot = 5M_\odot$ ($75R_\odot$ for $M_\odot = 60M_\odot$). The Roche lobe radius for the secondary is always greater than 22R\textsubscript{☉}, twice as large as the Wolf-Rayet star itself. Mass transfer by Roche lobe overflow is thus impossible, and the black hole must be accreting matter by capturing the thick stellar wind. Given the geometry of the system, the disk is very large, and thus there will be a helion partial ionization zone. Such a disk is prone to instability, causing the observed X-ray transient behaviours for M 101 ULX-1. In contrast, IC 10 X-1 and NGC 300 X-1 have shorter orbital periods (34.9 h and 32.3 h respectively) and smaller separations ($\sim 20R_\odot$). Because those Wolf-Rayet stars fill their Roche lobes, the black holes accrete via Roche-lobe overflow. These systems also have much smaller and hotter accretion disks without helium partial ionization zones, which explains why IC 10 X-1 and NGC 300 X-1 do not display disk-instability outbursts (see also Methods).

Mass transfer through wind accretion usually has a very low efficiency, as in the case of many low-luminosity, high-mass X-ray binaries, and is typically not considered for populations that require high accretion
Acknowledgements

We thank J. McClintock, R. Di Stefano, Q.-Z. Liu, X.-D. Li, F. Yuan and S.-N. Zhang for discussions. J.-F.L. acknowledges support for this work provided by NASA through the Chandra Fellowship Program (grant PF6-70043), support from the Chinese Academy of Sciences through grant KJCX2-EW-T01 and support by the National Science Foundation of China through grants NSFC-11273028 and NSFC-11333004. The paper is based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência, Tecnologia e Inovação (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina).

Author Contributions

J.-F.L. and J.N.B. proposed the observations, J.-F.L. and Y.B. reduced the data and carried out the analysis, J.-F.L., J.N.B. and S.J. discussed the results and wrote the paper, and P.C. helped to confirm the properties of the Wolf-Rayet star. All authors commented on the manuscript and contributed to the revision of the manuscript.

Author Information

Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to J.-F.L. (fliu@nao.cas.cn).
METHODS

Analysis of earlier M 101 ULX-1 observations. M 101 is a nearby face-on grand design spiral galaxy, a frequent target of various observations. These include the optical monitoring observations in search of Cepheids with the Hubble Space Telescope, yielding a distance of 6.855 Mpc (ref. 31). M 101 ULX-1 (C XO J10332.3+ 542103) is located near a spiral arm (Extended Data Fig. 1), and identified with a unique optical counterpart of V = 23.5 mag (ref. 32). At this location, the metallicity is 0.4 times solar according to the M 101 gas-phase oxygen abundance gradient. This ULX has been observed intensively by X-ray missions including ROSAT, XMM and Chandra since early 1990s, which exhibited spectral state transitions between the low-hard state and the high-soft state reminiscent of Galactic black-hole x-ray binaries. This ULX was once the brightest X-ray point source in M 101 with a Chandra/ACIS count rate of 0.10 counts s−1 (ref. 34), observed during the 2000 March observation (ObsID 934). The Chandra/XMM-Newton spectra during its outbursts were very soft and can be generally fitted with an absorbed blackbody model with neutral hydrogen column density nH = (1−4)×1022 cm−2 and temperatures of 50−100 eV, and the peak 0.3−7 keV luminosity reached 3×1040 erg s−1, with a bolometric luminosity of about 1041 erg s−1, suggesting an IMBH of a few thousand solar masses. It was argued that it is unphysical to adopt a high neutral hydrogen column density of nH = 1023 cm−2, and fitting the spectra as blackbody plus a disk-like component centred at 0.9 keV with nH fixed at the Galactic value of nH = 1020 cm−2 yielded the maximum outburst bolometric luminosity of 3×1048 erg s−1, consistent with the Eddington luminosity of a black hole of 20M⊙−40M⊙ (ref. 7).

The average line properties including FWHM, equivalent width, and line luminosities are measured from the combined spectrum (Extended Data Table 2). The shifts of the line centres were also measured for individual spectra, with the barycentric correction computed using the rvso package in IRAF as listed in Extended Data Table 1 for each spectrum. It was found that the line shifts, after barycentric correction, are consistent with being constant for narrow emission lines over all observations at 2.0±15 km s−1, consistent with the radial velocity of 241±2 km s−1 for the face-on M 101. However, the broad emission lines, as measured with the strongest HeII λ4686 Å shifted, from observation to observation between 210 km s−1 and 330 km s−1 as listed in Extended Data Table 1, with an average of 270 km s−1 that is significantly different from that for nebular lines.

The properties of the nebular lines help to determine the environmental metallicity and the neutral hydrogen column density. The line intensity ratio between [N II] λ6548 Å and [N II] λ5598 Å can be used as an abundance indicator with 12 + log(O/H) = 8.90 ± 0.57 ± N2, with a large dispersion in log(O/H) of ±0.41. Given the equivalent width of these two lines (Extended Data Table 2), we find 12 + log(O/H) = 8.70, close to solar metallicity (8.66). This is higher but marginally consistent with the value of 0.4 times solar according to the M 101 gas-phase oxygen abundance gradient given the location of ULX-1. The observed Balmer line flux ratios can be used to infer the dust extinction between the nebula and the observer. In the nebular emission around ULX-1, the intrinsic ratio Hb/Hα is 2.74 in case B for a thermal temperature of T = 20,000 K (ref. 38). Assuming E(B−V) = 0.1 mag, then Aα = 0.250 mag, Aγ = 0.360 mag, Aκ = 0.11 mag, Aν/HAγHκ = 1.1, and reddened Hb/Hα = 5. The observed Hb/Hα is 2.85, suggesting that the extinction is low, and using the Galactic value is reasonable.

Determining the Wolf-Rayet subclass of binary ULX-1. The broad helium emission lines in the newly obtained Gemini/GMOS spectrum are of an extremely hot, hydrogen-depleted Wolf-Rayet star. Accretion disks around a compact object can also give rise to broad helium emission lines, but a broad Balmer line is expected to be weak or much stronger than the helium lines. In the GMOS spectrum, emission lines are present in two ULXs with optical spectra (4,000~5,400 Å), NGC 1313 X-24 and NGC 5408 X-1, and are stronger than the He II 4,686 Å emission line. In the ULX-1 spectrum (Fig. 1), although the Balmer emission lines are present, they are narrow emission lines like forbidden lines, and should come from the surrounding nebula, as evidenced by their nearly constant line shifts from observation to observation, in distinct contrast to helium lines with line shift differences of ±60 km s−1.

The sub-type of this Wolf-Rayet star can be determined from the presence or absence of line species in the spectrum. There are two main types of Wolf-Rayet stars, WN stars with [N II] λ5598 Å and [N II] λ6548 Å, can be used as an abundance indicator with 12 + log(O/H) = 8.90 ± 0.57 ± N2, with a large dispersion in log(O/H) of ±0.41. Given the equivalent width of these two lines (Extended Data Table 2), we find 12 + log(O/H) = 8.70, close to solar metallicity (8.66). This is higher but marginally consistent with the value of 0.4 times solar according to the M 101 gas-phase oxygen abundance gradient given the location of ULX-1. The observed Balmer line flux ratios can be used to infer the dust extinction between the nebula and the observer. In the nebular emission around ULX-1, the intrinsic ratio Hb/Hα is 2.74 in case B for a thermal temperature of T = 20,000 K (ref. 38). Assuming E(B−V) = 0.1 mag, then Aα = 0.250 mag, Aγ = 0.360 mag, Aκ = 0.11 mag, Aν/HAγHκ = 1.1, and reddened Hb/Hα = 5. The observed Hb/Hα is 2.85, suggesting that the extinction is low, and using the Galactic value is reasonable.

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The best solution is found at the minimum $\chi^2 = 1.6$, for which the best period $P = 8.24 \pm 0.1$ days and the best radial velocity semi-amplitude $K = 61 \pm 5$ km s$^{-1}$, with the 68.3% error determined with $\Delta \chi^2 = 1$. The fact that the radial velocity curve can be fitted with a sine curve suggests that the orbital eccentricity is small.

Given $P$ and $K$, the mass function for M101 UX-1 can be computed as $f(M_*, M) = \frac{P^3}{2\pi G} (\frac{M_1}{M + M}) \sin i = 0.178M_\odot$. This sets an absolute lower limit for the mass of the primary. In the case of UX-1, more information can be extracted because we already know $M_1 = 19M_\odot$. Given the equation $\frac{M_1^3}{M + M_1} \sin i = 0.178M_\odot$, the primary mass will increase monotonically when the inclination angle decreases, that is, changing from edge-on ($i = 90^\circ$) towards face-on ($i = 0^\circ$). Thus the minimum mass for the primary can be obtained when $i = 90^\circ$, which is $M_1 = 4.6M_\odot$ after solving the equation $\frac{M_1^3}{M + M_1} \sin i = 0.178M_\odot$.

The minimum mass will be $M_1 = 4.4M_\odot$ if we use $M_1 > 17.5M_\odot$. Such a compact primary can only be a black hole. This is thus the dynamical evidence for a black hole in a ULX.

Determining the properties of the Wolf-Rayet/black-hole binary. This section duplicates some text from the main article, but with additional technical details.

M101 UX-1 is thus a Wolf-Rayet/black-hole binary, only the third discovered so far after IC 10 X-1 and NGC300 X-1. The binary separation can be computed with Kepler’s law $a^3 = \frac{GM_1M_\odot}{2\pi^2}\frac{P^2}{4}$, which increases monotonically for increasing black-hole mass, starting from $a = 50R_\odot$ for $M_1 = 4.6M_\odot$ to $a = 75R_\odot$ for $M_1 = 60M_\odot$ (Extended Data Fig. 3). The Roche lobe size for the secondary can be computed with $R_L = qV(q) = (0.49q^2)(1.06q^2 + 1 (q + q^2))$ with $q = M_1/M_\odot$, and the Roche lobe size for the black hole can be computed with the same formula but with different $q = M_1/M_\odot$. As shown in Extended Data Fig. 3, the Roche lobe size for the black hole increases with the increasing black-hole mass, but the Roche lobe size for the secondary does not change much, from $R_L = 25R_\odot$ for $M_1 = 4.6M_\odot$ to $R_L = 23R_\odot$ for $M_1 = 10M_\odot$, and to $R_L = 22R_\odot$ for $M_1 = 30M_\odot$.

Regardless of the black-hole mass, the secondary is filling only half of its Roche lobe by radius, and the black hole must be accreting from the Wolf-Rayet star winds. Because the black hole is at least $50R_\odot$ away from the Wolf-Rayet star, the stellar wind will have reached close to its terminal velocity. The capture radius for the wind accretion can be computed as $r_{\text{acc}} = \frac{2GM_1}{v_c^2}$ and the accretion rate can be computed as $\dot{M}_\text{acc} = \pi r_{\text{acc}}^2 v_c$. Given that the average luminosity for M101 UX-1 is about $3 \times 10^{37}$ ergs s$^{-1}$, the required accretion rate is $\dot{M}_\text{acc} = L/\eta = 3 \times 10^{-3} \times 9 \times 10^{-5} = 6 \times 10^{-3}M_\odot$ yr$^{-1}$. To capture this much stellar wind matter, as shown in Extended Data Fig. 4, the black-hole mass must be greater than 46$M_\odot$ for $\eta = 0.06$ in the case of a non-spinning Schwarzschild black hole, and greater than 13$M_\odot$ for $\eta = 0.42$ in the case of a maximally spinning Kerr black hole. If we use the velocity law $v(\theta) = v_c(1 - \beta \cos \theta)$ with $\beta = 0.1$ for the inner wind$^4$, then the black-hole mass must be greater than 28$M_\odot$ for $\eta = 0.06$ in the case of a non-spinning Schwarzschild black hole, and greater than 8$M_\odot$ for $\eta = 0.42$ in the case of a maximally spinning Kerr black hole. If we adopt a typical $\eta$ value of 0.1, the required accretion rate corresponds to $\dot{M}_\text{acc} > 24M_\odot$ (and $i < 17^\circ$) for a wind velocity of $v = 1100$ km s$^{-1}$, and corresponds to $\dot{M}_\text{acc} > 32M_\odot$ (and $i < 14^\circ$) for the terminal velocity. The accretion rate argument thus requires a black hole of $> 8M_\odot$--$46M_\odot$, likely to be a black hole of $20M_\odot$--$30M_\odot$ similar to IC 10 X-1 and NGC 300 X-1.

The recurring X-ray/optical outbursts dictate the presence of an accretion disk prone to instability, and the disk formation under stellar wind accretion places stringent constraints on the binary system. To explore why the number of Galactic X-ray stars is so small, it has been shown$^{37}$ that in the case of accretion of stellar wind matter in a detached binary system the specific angular momentum of the matter captured by the compact object is typically small. Therefore, usually no accretion disk is formed around the compact object. Consequently, very special conditions are required for a black hole in a detached binary system to be a strong X-ray source. A disk may form if the specific angular momentum of accreting matter, $Q_{\text{acc}} = \frac{\ell_{\text{acc}}}{M_{\text{acc}}}$, exceeds the specific angular momentum of the particle at the innermost stable circular orbit, $Q_{\text{ISCO}} = \sqrt{\frac{GM_{\text{acc}}}{c^2}}$. This is usually expressed as $P < 4.8 \times 10^{51} M_{\text{acc}}^2 \ell_{\text{acc}}^2$, where $\delta = 1$ is a dimensionless parameter$^{38,49}$. Given $P = 8.24 \pm 0.1$ days and $v_c = 1300 \pm 100$ km s$^{-1}$ for M101 UX-1, the black-hole mass is required to be $M_1 > 80M_\odot$, corresponding to $i = 9^\circ$ (that is, nearly face-on). If the wind velocity from the velocity model of the inner wind$^{38}$ is adopted, then the black-hole mass is required to be $M_1 > 48M_\odot$, corresponding to $i = 11^\circ$.
To investigate the possible presence of a partial ionization zone, we need to compute the temperature structure $T_d(r)$ for the accretion disk, especially for the outer disk. Following the procedures designed for an X-ray irradiated black-hole binary model for ULXs\cite{35}, we compute the disk temperature structure for a standard accretion disk with the $x$ prescription\cite{36} plus X-ray irradiation.\cite{37} As shown in Extended Data Fig. 5, regardless of the black-hole mass for M 101 ULX-1, its outer disk temperature is as low as 4,000 K in the low-hard state owing to its large separation and large disk, and the helium partial ionization zone at about 15,000 K is bound to exist unless the black-hole mass is lower than $5.5 M_\odot$. In comparison, the disk temperature for NGC 300 X-1, with an orbital period of 32.8 h and its WN5 star ($M_* = 26 M_\odot$, $R_* = 7.2 R_\odot$) filling its Roche lobe\cite{38}, never drops below 20,000 K owing to its small separation and small disk, and there is no helium partial ionization zone in the disk. This explains naturally why NGC 300 X-1 and similarly IC 10 X-1 exhibit steady X-ray radiation despite the apparent variations due to orbital modulation under the edge-on viewing geometry.

The existence of an accretion disk in M 101 ULX-1 is also supported by the observed spectral state changes, which resemble those for Galactic black-hole binaries\cite{39,40} that are believed to reflect changes in the properties of their accretion disks\cite{41}. During its outbursts, M 101 ULX-1 exhibits an X-ray spectrum\cite{42} that can be classified as a thermal dominant state (albeit with exceptionally low disk temperatures), a well-defined spectral state that corresponds to a standard thin accretion disk at about 10% of its Eddington limit, the emission changes such that the X-ray spectrum includes a steep power-law with a significant hard component above 2 keV. The presence of such a hard component is not seen in the X-ray spectra of M 101 ULX-1. Given its bolometric luminosity of $3 \times 10^{39} \text{erg s}^{-1}$ in the thermal dominant state at less than 30% of its Eddington limit, we infer that the black-hole mass is above 80$M_\odot$. If this is true, the inferred black-hole mass of M 101 ULX-1 may challenge the expectations of current black-hole formation theories.

The optical counterpart of M 101 ULX-1.\cite{43} The most massive black holes that can be produced for solar metallicity are about $15 M_\odot$, and about 20$M_\odot$ ($25 M_\odot$, $30 M_\odot$) for $0.6$, $0.4$, $0.3$ solar metallicity owing to reduced stellar winds and hence reduced mass loss in the final stages before stellar collapse.\cite{44,45,46}

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Extended Data Figure 1 | M 101 ULX-1 as observed in the optical region.
Left, M 101 ULX-1 is located on a spiral arm of the face-on grand-design spiral galaxy M 101, as indicated by the arrow. The colour image of M 101 is composed of GALEX NUV, SDSS g, and 2MASS J images. Right, ULX-1 is identified as a blue object with $V = 23.5$ mag at the centre of the 1'' circle on the HST image. The colour image is composed of ACS/WFC F435W, F555W and F814W images.
Extended Data Figure 2 | Physical properties of the Wolf-Rayet secondary from spectral line modelling. Distributions of computed \( \Delta^2 \) as a function of stellar masses (a), stellar mass loss rate (b), stellar radii (c) and terminal velocity (d). Here \( \Delta^2 = \sum (EW - EW^*)^2 \) computes the difference between observed and synthetic equivalent widths EW for six broad helium lines present in the Gemini/GMOS spectrum. We have computed synthetic spectra for a group of 5,000 real stars from the evolution tracks (as shown by the thick stripes in the mass plot and the radius plot) and for another group of 'fake' stars with continuous distributions in mass, radius and luminosity. The best model is labelled by a filled pentagon in all panels.
Extended Data Figure 3 | Properties of the Wolf-Rayet/black-hole binary for different black-hole masses. Shown are the binary separation (solid line), the Roche lobe sizes for the Wolf-Rayet star (dotted) and for the black hole (short dashed), the capture radius for the black hole when using the terminal velocity (dash–dotted) or when using a simplified velocity law $\nu(r) = \nu_\infty (1 - R/r)$ (long dashed).
Extended Data Figure 4 | The black-hole accretion rate for different black-hole masses. The accretion rates are computed adopting the terminal velocity (dotted) and a simplified velocity law \( v(r) = v_\infty (1 - R_*/r) \) (solid). To power the observed average luminosity of \( 3 \times 10^{38} \text{ erg s}^{-1} \), the black-hole mass must exceed \( 13M_\odot (8M_\odot) \) using the terminal velocity (the velocity law) for a Kerr black hole (\( \eta = 0.42 \)), and exceed \( 46M_\odot (28M_\odot) \) for a Schwarzschild black hole (\( \eta = 0.06 \)). The two horizontal dotted lines indicate the accretion rates required for \( \eta = 0.06 \) and \( \eta = 0.42 \), respectively.
Extended Data Figure 5 | Disk temperature structures for M 101 ULX-1.
a. The disk temperature profiles for M 101 ULX-1 (for $P = 8.24$ days, $M_\ast = 19M_\odot$, $R_\ast = 10.7R_\odot$, $M_\ast = 10M_\odot$ or $100M_\odot$) and NGC300 X-1 (for $P = 32.4$ h $M_\ast = 26M_\odot$, $R_\ast = 7.2R_\odot$, $M_\ast = 16.9M_\odot$; ref 22). b. The disk temperature at the outer edge for different black-hole mass in M 101 ULX-1. The horizontal line indicates the temperature required for the helium partial ionization zone.
Extended Data Table 1 | Gemini/GMOS spectroscopic observations of M 101 ULX-1

| OBSDATE   | MJD       | exposure (second) | bary. (km/s) | velocity (km) |
|-----------|-----------|-------------------|--------------|---------------|
| 2010-02-15| 55242.58343| 3200              | 7.4          | 212           |
| 2010-02-16| 55243.50615| 3200              | 7.3          | 236           |
| 2010-03-16| 55271.54390| 3200              | 0.1          | 301           |
| 2010-03-17| 55272.54564| 3200              | -0.2         | —             |
| 2010-04-17| 55303.47547| 4800              | -7.7         | 326           |
| 2010-05-13| 55329.33126| 6400              | -12.2        | 302           |
| 2010-05-14| 55330.39682| 6400              | -12.4        | 256           |
| 2010-05-15| 55331.37803| 6400              | -12.5        | 227           |
| 2010-05-18| 55334.41410| 9600              | -13.0        | 244           |
| 2010-05-19| 55335.42301| 9600              | -13.1        | 305           |

The columns are: (1) observation date, (2) modified Julian date, (3) exposure time in seconds, (4) barycentric correction computed with rvsao, and (5) the corrected radial velocity as measured with He II 4,686 Å, with an error of 15 km s\(^{-1}\) as mainly from the uncertainties in the wavelength calibration.
Extended Data Table 2 | Properties of emission lines

| Line ID | FWHM (Å) | E.W. (Å) | Lum. $10^{34}$ erg/s | model (Å) |
|---------|----------|----------|----------------------|-----------|
| HeII 4686 | 19.3 | 21.83 ± 0.20 | 43 | 21.75 |
| HeI 5876 | 19.0 | 34.78 ± 0.29 | 49 | 34.21 |
| HeI 6679 | 18.8 | 25.74 ± 0.37 | 24 | 26.56 |
| HeII 5411 | 20.5 | 5.46 ± 0.13 | 8.3 | 6.10 |
| HeI 4922 | 13.4 | 5.80 ± 0.64 | 8.4 | 3.91 |
| HeI 4471 | 12.1 | 3.86 ± 0.65 | 7.0 | 5.18 |
| $H_\alpha$ | 3.6 | 1.35 ± 0.22 | 2.7 | |
| $H_\beta$ | 4.5 | 7.51 ± 0.06 | 12 | |
| $H_\gamma$ | 4.7 | 26.54 ± 0.46 | 34 | |
| [OIII] 4960 | 4.4 | 23.70 ± 0.49 | 40 | |
| [NII] 6548 | 3.8 | 3.85 ± 0.39 | 4.7 | |
| [NII] 6583 | 4.7 | 16.66 ± 0.08 | 18 | |
| [SII] 6716 | 4.0 | 4.58 ± 0.07 | 4.0 | |
| [SII] 6731 | 4.6 | 3.81 ± 0.06 | 3.1 | |

The columns are: (1) emission line ID, (2) FWHM as obtained from Gaussian fit, which equals 2.35s, (3) equivalent width, (4) line luminosity in units of $10^{34}$ erg s$^{-1}$, and (5) equivalent width from the best Wolf-Rayet synthetic model.