An evolving jet from a strongly magnetized accreting X-ray pulsar

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Relativistic jets are observed throughout the Universe and strongly affect their surrounding environments on a range of physical scales, from Galactic binary systems1 to galaxies and clusters of galaxies2. All types of accreting black hole and neutron star have been observed to launch jets3, with the exception of neutron stars with strong magnetic fields4,5 (higher than 1012 gauss), leading to the conclusion that their magnetic field strength inhibits jet formation6. However, radio emission recently detected from two such objects could have a jet origin, among other possible explanations7,8, indicating that this long-standing idea might need to be reconsidered. But definitive observational evidence of such jets is still lacking. Here we report observations of an evolving jet launched by a strongly magnetized neutron star accreting above the theoretical maximum rate given by the Eddington limit. The radio luminosity of the jet is two orders of magnitude fainter than those seen in other neutron stars with similar X-ray luminosities9, implying an important role for the properties of the neutron star in regulating jet power. Our result also shows that the strong magnetic fields of ultra-luminous X-ray pulsars do not prevent such sources from launching jets.

On 3 October 2017, the Neil Gehrels Swift Observatory (Swift) detected an outburst of a new X-ray transient Swift J0243.6+6124 (hereafter Sw J0243)10. The discovery of 9.86-s pulsations11 identified this transient as an accreting pulsar: a relatively slowly spinning neutron star with a strong magnetic field (B ≥ 1012 G)12, probably accreting from a high-mass companion Be star. Throughout its outburst, we observed this source at radio wavelengths over eight epochs with the Karl G. Jansky Very Large Array (VLA); see Fig. 1. After an initial non-detection early in the outburst, we detected significant (18.3σ) radio emission at 6 GHz close to the X-ray peak (Fig. 2), when the neutron star was accreting above the theoretical Eddington limit. The radio luminosity of the system subsequently decayed with the X-ray flux, while the radio spectral index α (where the flux density is Sν ∝ να) gradually evolves throughout the outburst. We did not detect linearly polarized emission during any epoch, with a very stringent upper limit of about 15% during the third observation (Extended Data Tables 1 and 2 for all measurements).

Its radio properties show that Sw J0243 launches an evolving jet. Whenever accreting compact objects launch steady jets, the radio and X-ray luminosity are coupled13,14 (see Fig. 3), indicating a direct relationship between the X-ray-emitting accretion flow and the radio-emitting jet. After the initial radio non-detection, we observed such a coupling between the X-ray and radio luminosities of Sw J0243, with the radio luminosity decreasing as the X-ray luminosity of the outburst decayed. By estimating the correlation index between the 0.5–10-keV X-ray and 6-GHz radio luminosities, we measured Lx ∝ Lr0.54±0.16, which is consistent with both black-hole and neutron-star X-ray binaries14 (see Methods).

The radio spectral shape and evolution also support a jet origin of the outburst. In radiofrequencies, jets launched from stellar-mass accretors emit synchrotron radiation with a spectral index that can vary over time, as observed in Sw J0243. The radio spectral index distribution of Sw J0243 starts out steep (α < 0) and gradually evolves to a flat spectrum (α ≥ 0), as observed in canonical steady X-ray binary jets15. This systematic evolution during the outburst decay can be interpreted as follows: during the super-Eddington phase, where strong outflows are expected theoretically16, discrete transient ejecta were launched. When the accretion rate decayed during the remainder of the outburst, the radio–X-ray correlation and the transition towards an inverted spectrum signalled that the radio emission arose from a compact, steady jet instead15. Alternatively, a gradual shift of the break frequency, where the jet spectrum transitions from optically thin to thick synchrotron radiation, could also be responsible for the observed evolution of the radio spectral index. As discussed in Methods, alternative physical or emission mechanisms cannot explain the observed combination of spectral index evolution, flux levels, radio–X-ray coupling and polarization. We note that both the observed polarization properties and the spectral shape and evolution rule out coherent radio pulsations being responsible for the radio emission.

Before our radio monitoring campaign of Sw J0243, jets had been confirmed in all types of X-ray binary systems17 except in strongly magnetized accreting pulsars, which are the most common X-ray binary type. Multiple large surveys in the 1970s and 1980s failed to detect radio emission from these systems18,19, leading to the observational notion that their strong magnetic field prevents the formation of jets. Until recently, searches for radio emission from individual neutron stars with such field strengths also yielded non-detections16, further strengthening this idea. As a result, strongly magnetized accreting neutron stars are often disregarded in theoretical studies of neutron-star jet formation19.

Jet formation models developed for accreting neutron stars commonly invoke a magneto-centrifugal launch mechanism6,20,21, in which the jet is launched by field lines anchored in the innermost accretion disk. Such models offer a straightforward theoretical explanation for the prevention of jet formation by strong magnetic fields: the neutron-star magnetosphere stops the formation of the inner accretion flow by dominating over the disk pressure6, therefore preventing the launching of a jet. The first observational results to question this view were the recent radio detections17,18 of the two strongly magnetized pulsars Her X-1 and GX 1+4. However, in contrast to our Sw J0243 observation, both sources were detected at a single frequency during a single epoch, meaning that the origin of the emission remained ambiguous. Given the lack of information on spectral shape, temporal evolution or coupling with the X-ray flux, a jet could neither be excluded nor directly inferred. Moreover, the properties of any putative jets—if present—could not be determined from the limited information available.

Our clear discovery of an evolving jet in Sw J0243 disproves the long-standing idea that strong magnetic fields prevent the launch of a jet. This directly indicates that existing models of jet formation in neutron-star X-ray binaries6–20 need to be revisited. For instance, the jet-launching region must be much farther from the neutron star than in other classes of jet-forming systems. The presence of X-ray images...
Conservatively estimated, its minimum size—at the outburst peak, accretion flow, channelling the material to the neutron-star poles.

Fig. 1 | Radio and X-ray outburst light curve of Sw J0243. a. Radio flux densities detected by the VLA at 6 GHz and 22 GHz (red circles and blue squares; right axis) and the count rate between 15 keV and 50 keV measured by the Burst Alert Telescope (BAT) onboard Swift throughout the outburst (grey pentagons; left axis). Sw J0243 was not detected during the first radio epoch, marked by downward arrows. b. Radio spectral index $\alpha$ (flux density, $S \propto \nu^\alpha$) as a function of time. In both panels error bars are given at the 1σ level and upper limits are 3σ.

Our discovery of a jet in a strongly magnetized accreting pulsar has two additional major implications. First, it implies that accreting pulsars form a large, hidden class of radio emitters, which are now accessible through the current generation of observatories with upgraded sensitivities. This unexplored population opens up new avenues to test general predictions of jet theory for all accreting systems. In Blandford–Znajek-type models for black holes, and not launched by field lines in the inner accretion disk, as in the magneto-centrifugal (Blandford–Payne-type) jet models commonly used for neutron stars.

This model, which was subsequently shown by numerical simulations to be applicable to the super-Eddington accreting regime of Sw J0243, also predicts a suppression of two orders of magnitude in jet power for slowly pulsating, strongly magnetized accreting pulsars compared to their weakly magnetized, rapidly spinning counterparts.

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in spin and have similar and well measured magnetic fields. Now that we have found that strongly magnetized accreting pulsars can launch jets, future observational campaigns of this source class will probe the predicted relation between spin and jet power.

In addition, the detection of a jet in Sw J0243 expands the possible types of outflow in ultra-luminous X-ray sources (ULXs), which are binary systems with X-ray luminosities greatly exceeding the Eddington luminosity of a stellar-mass accretor. Super-Eddington winds have previously been observed in both black-hole and neutron-star ULXs8, and jets have been inferred in a handful of black-hole ULXs through direct detection and the presence of surrounding bubbles27. Although several ULXs have been confirmed to be neutron stars at super-Eddington rates30, such as Sw J0243. Our detection of a large fraction of the population. Interestingly, the known ULX pulsars show similar X-ray behaviour to Galactic pulsars accreting from Be stars at super-Eddington rates28, such as Sw J0243. Our detection of a jet in Sw J0243 therefore implies that, in addition to winds, ULX pulsars might also launch jets, unharnessed by their strong magnetic fields.

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Radio observations. We observed Sw J0243 with the VLA over eight epochs between 10 October 2017 and 9 January 2018. The observations were part of two Director's Discretionary Time programmes, VLA/17B-406 and VLA/17B-420, for the first two and remaining six epochs, respectively. The total observing time was 13 h. In two observations, we observed the target only at the C band, centred at 6 GHz with 4 GHz of bandwidth. In the other six observations, we observed both at the C band (with the same setup) and K band, with the latter centred at 22 GHz with 8 GHz of bandwidth. Detailed information about each epoch can be found in Extended Data Table 1.

In all epochs, the primary calibrator was J0137+331 (3C48) and the nearby phase calibrator was J0244+6228 (1.04° angular separation from the target). When included in the setup (epochs 3–7), the leakage calibrator was J0319+4130 (3C84). For the target field, the centre was offset by 6'' in the north direction from the detection position of the XRT onboard Swift to prevent possible correlated artefacts at the phase centre from affecting the results. During all observations, the VLA was in its B configuration. More detailed information, such as beam sizes and position angles in each observing band and epoch, is given in Extended Data Table 1.

To analyse the observations, we used the Common Astronomy Software Application package (CASA) v4.7.2 to flag, calibrate and image the data. We removed radio–frequency interference using a combination of automated flagging routines and careful visual inspection. Given the lack of bright radio emission in the target field, we did not self-calibrate. Using the multi-frequency multi-scale CLEAN task with Briggs weighting and a robustness of 1 (to reduce the effects of the side-lobes of a neighbouring source), we imaged Stokes I at all observed frequencies for all epochs, and Stokes Q and U at 6 GHz for epochs with leakage calibration. We did not image Stokes Q and U at 22 GHz because we did not detect any linearly polarized emission at 6 GHz. Therefore, no such emission is expected at 22 GHz, and the better r.m.s. sensitivity at 6 GHz yields tighter upper limits. Accreting X-ray binaries are expected to be unresolved point sources for the VLA. Therefore, we determined fluxes by fitting an elliptical Gaussian equaling the beam size to the source in the image plane. We measured the RMS of the cleaned image over a region close to the target position. We determined a single flux density in each band and, owing to the faintness of the radio emission, did not divide the C- and K-band frequency ranges further. A quick check for time variability did not reveal any evidence for substantial variability within observations.

The target was not detected in our first observational epoch, with >3 upper-limits on the flux densities of 12 μJy per beam and 9 μJy per beam in the C and K band, respectively. Sw J0243 was detected in all following observations. All flux densities are listed in Extended Data Table 2. The radio position of Sw J0243, measured at 6 GHz from the first detection, is RA = 02 h 43 min 40.440 s ± 0.029 s and dec. = +61°26′03.73″ ± 0.10″.

All positions determined from the radio detections are consistent with the Swift-XRT X-ray position in the X-ray band. In Extended Data Fig. 1, we show the target field during the initial non-detection and the first detection. The combination of the spatial coincidence between the X-ray and radio position and the coupled X-ray and radio variability shows that the observed radio emission originates from Sw J0243.

In epochs with both C- and K-band observations, we calculated the spectral index to investigate the spectral shape. The power-law spectral index $\alpha$ (where the flux density is $S_{\nu} \propto \nu^{\alpha}$) between two frequencies $\nu_1$ and $\nu_2$ with corresponding flux densities $S_{\nu_1}$ and $S_{\nu_2}$ is calculated as:

$$\alpha = \frac{\log(S_{\nu_1}/S_{\nu_2})}{\log(\nu_1/\nu_2)}$$

To calculate the uncertainty on the spectral index for each individual epoch, we propagate the uncertainties on the measured flux densities and the range in frequencies through a Monte Carlo simulation; in each iteration, we perform 10 iterations.

X-ray flux measurements. For the study of Sw J0243 in the X-ray luminosity–radio luminosity plane, accurate and precise X-ray fluxes during the radio epochs are required. Three X-ray instruments consistently observed the entire outburst of Sw J0243: the XRT and Burst Alert Telescope (BAT) instruments onboard Swift32 and the Monitor of All-sky X-ray Image (MAXI) onboard the International Space Station. The BAT and MAXI are monitoring instruments, whereas XRT exposures are pointed observations. Both monitoring instruments only provide count rates of observed targets, which cannot be converted to a flux straightforwardly without knowing the shape of the X-ray spectrum. The comparison of XRT fluxes and monitoring count rates shows that the broadband X-ray spectral shape evolves during the outburst. This implies that the count-rate-to-flux conversion for the BAT and MAXI is also variable and therefore makes both instruments inconvenient for accurately estimating the X-ray flux. The MAXI is additionally unsuitable because a visual inspection of the light curve shows several unpulsive jumps in count rate, pointing towards systematic errors in the monitoring.

The above considerations make the XRT the most reliable instrument to determine the X-ray flux of Sw J0243 during the radio epochs. Five out of the eight radio epochs had quasi-simultaneous X-ray flux coverage (within 2 days). For the remaining three epochs, such XRT observations were not available. However, preliminary flux estimates for all XRT observations, extracted using the Swift-XRT data products generator34 (http://www.swift.ac.uk/user_objects/), show that Sw J0243 decayed in a steady, log-linear fashion as a function of time. Therefore, for the three radio epochs without close XRT coverage, we estimated the logarithm of the X-ray flux by linear interpolation between the logarithmic fluxes of the preceding and subsequent XRT pointings. Before describing the actual X-ray flux measurements, we stress that the BAT count rate of Sw J0243 between 15 keV and 50 keV also decayed in a log–linear fashion during our radio monitoring. This implies that the XRT observations, which only provide spectra up to 10 keV, are representative of both the soft- and hard-X-ray decay of Sw J0243.

We extracted spectra from the radio position of Sw J0243 using the Swift-XRT data products generator34 and used XSPEC35 v12.9.0 to fit the data and determine the fluxes. All analysed observations were taken in the window–timing mode. We did not use the fluxes provided by the data products generator for our actual measurements; these fluxes are based on a power-law–only model, which is not necessarily accurate for every spectrum. Moreover, the automatic fits are performed between 0.3 and 16 keV whereas the window–timing mode of XRT is subject to calibration uncertainties for moderately–to heavily absorbed sources, possibly resulting in poor fits at low energies (see, for example, http://www.swift.ac.uk/analysis/xrt/digest_cal.php#abs).

We fitted each spectrum with a model containing interstellar absorption, a blackbody component and a power law (TBABS(BBODYRAD+PO)). Because Be/X-ray binaries can have strongly variable local absorption, we did not tie the absorption column between spectra. We assumed Wilms abundances36 and Verner cross-sections37 and fitted the spectra in the reliable energy range (0.7–10 keV). We then determined unabsorbed fluxes and their uncertainties in the 0.5–10 keV range using CELUX and the best-fitting model. Information on the analysed observations and the fluxes determined in this analysis, including interpolated fluxes, are listed in Extended Data Table 3. The best-fit parameters for each spectrum are listed in Extended Data Table 4.

Gaia distance measurement. We used the recent Gaia Data Release 238–30 to obtain an independent measurement of the distance to the system. The measured parallax of Sw J0240 is $\pi = 0.0952 \pm 0.0302$ mas. We followed the standard Bayesian method to infer the distance towards the system25. The likelihood function assumes a functional form for the distance–parallax relation and a distribution of parallaxes and a distribution modellled as an exponential decreasing volume density function, with a length scale of 1.35 kpc corresponding to the line-of-sight value41. We took into account the zero point from the global astrometric solution $\alpha_{2015} = -0.029$ mas and we used a Markov chain Monte Carlo procedure (as implemented in entice43) to sample the posterior distribution of the distance. The marginal posterior distributions are shown in Extended Data Fig. 1. We found a median value of $D = 7.3$ kpc with 16th and 84th percentiles of 6.1 kpc and 8.9 kpc, respectively. We stress that the posterior distribution is not symmetric and caution should therefore be exercised in using these numbers.

Given the large fractional error of the parallax, the shape of the posterior distribution deviates from a Gaussian distribution and the upper tail is very sensitive to the choice of the prior distribution. We investigated the robustness of our distance estimate with different choices of prior distributions, as shown in Extended Data Fig. 1. When using a uniform prior with a maximum distance of 50 kpc, the median of the distribution shifts towards larger distances. However, the lower limit of the distance is greater than 5.0 kpc at >99% confidence level for both priors. Therefore, the Gaia measurement shows that the source is located at a distance of at least 5.0 kpc, independent of the prior used. We conservatively adopt this lower limit on the distance in Fig. 3.

During the peak of the outburst, around the time of the first radio detection (epoch 2), the XRT unabsorbed flux at 0.5–10 keV (3.69 ± 0.03) × 10−10 erg s−1 cm−2; For a conservative (prior-independent) minimum distance to the source of 5 kpc, this flux corresponds to an X-ray luminosity of $1.1 \times 10^{39} \times [D/(5\,\text{kpc})]^{2}$ erg s−1. If we apply a bolometric correction, by extrapolating the best-fitting model to the 0.1–100 keV range, we find an even higher luminosity of $5 \times 10^{39} \times [D/(5\,\text{kpc})]^{2}$ erg s−1. The theoretical Eddington luminosity of an accreting neutron star is $L_{\text{Edd}} = 1.3 \times 10^{38} \times [M/(1\,\text{M}_\odot)] \times [D/(5\,\text{kpc})]^{2}$ erg s−1. The ratio of the measured luminosity to the theoretical Eddington luminosity is $L/L_{\text{Edd}} = 0.6$, which is consistent with the Luminosity Distance Relation

Swift-BAT light curve. To show the long-term X-ray evolution of Sw J0243, we display the Swift-BAT light curve in Fig. 1; however, for clarity, we show a cleaned

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version of this light curve. Owing to the extremely high count rates of the source, the measured count rate sometimes dropped by an order of magnitude in individual exposures—the BAT team ascribes these drops to software issues and not to intrinsic variability in Sw J0243 (https://swift.gsfc.nasa.gov/results/transients/weak/SwiftJ0243.66p124/). Therefore, we masked these anomalously low points in the light curve, which occur between 19 and 60 days into the outburst, around the times with the highest count rates. In this time interval the actual rates exceeded 0.7 counts per second, so we removed all exposure with lower count rates. We stress that this cleaning procedure is for visual purposes only and does not affect our actual measurements or conclusions.

**Estimating the magnetospheric radius.** The magnetospheric radius is defined as the radius where the pressure of the magnetosphere and accreting material are equal. Therefore, this radius will depend on the strength of the magnetic field, \( B \), and the rate of accretion. The latter can be estimated from the bolometric flux, \( F \), the distance, \( D \) (together providing the X-ray luminosity), the accretion efficiency, \( \eta \) (which converts the mass-accretion rate to luminosity) and an anisotropy correction factor, \( f \), which accounts for the anisotropy of the emitted X-rays. Finally, the type of accretion (that is, wind or disk) has to be taken into account through a geometrical correction factor, \( k \). For standard neutron-star parameters—a mass of 1.4 \( M_\odot \) and a radius of 10 km—the magnetospheric radius \( R_m \) (in gravitational meters, \( G = 6.674 \times 10^{-11} \text{cm}^3\text{g}^{-1}\text{s}^{-2} \)) is provided from the X-ray luminosity of the source, \( L_x \), and with the existing literature.

\[
R_m = \left( \frac{B}{1.2 \times 10^8 \text{G}} \right)^{4/7} \left( \frac{f}{\eta} \right)^{1/4} \left( \frac{F}{10^{-7} \text{erg s}^{-1} \text{cm}^{-2}} \right)^{1/4} \left( \frac{D}{5 \text{kpc}} \right)^{4/7} \left( \frac{R_g}{\text{m}} \right)
\]

Although not all parameters are known precisely, we can use this equation to estimate a minimum size of the magnetosphere during the outburst. The maximum unabsorbed, bolometric X-ray flux observed by Swift-XRT around a radio epoch, which will give the smallest magnetospheric radius, is 4.9 \( \times 10^{-7} \text{erg s}^{-1} \text{cm}^{-2} \) (but see below). Gaia measurements with an exponential prior distribution imply a median distance estimate of 7.3 kpc, which we adopt for this calculation—this provides a more conservative lower limit on \( R_m \) than using a minimum distance of 5 kpc. The minimum value of \( k \) is 0.5, as appropriate for disk accretion. The accretion efficiency is typically assumed to be 0.1, and the anisotropy correction is close to unity. Finally, the magnetic field is not measured directly but can be determined from the X-ray pulsations to exceed 10 \( ^{14} \) G. Combining these numbers yields \( R_m \geq 2 \times 50 \mu \text{m} \) (that is, about 670 km).

Following typical assumptions, we used the bolometric X-ray flux, combined with an efficiency of 10\%, to probe the mass-accretion rate that balances the magnetic pressure. However, a non-negligible fraction of the X-ray flux might be emitted from the neutron-star surface with higher efficiency, which would imply that this approach might overestimate the mass-accretion rate. On the other hand, outflows from the neutron star or disc could cause the flux-derived mass-accretion rate to be underestimated. Given these contradictory possibilities, we did correct for either of these processes: correcting for the former would lead to a larger magnetospheric radius, which is already consistent with our approach of calculating a lower limit; correcting for the latter would lead to a lower radius—but this correction is small, given the weak scaling between mass-accretion rate and magnetospheric radius (\( \sim 2/7 \)). Thus, correcting for either case does not affect our conclusions.

**Radio–X-ray correlation sample.** For the radio–X-ray correlation, shown in Fig. 3, we use a comprehensive sample of hard-state Atoll neutron-star sources and hard-state black holes from the large body of observational studies of X-ray binaries performed over the past decades. This sample is freely available online (https://jakobvdeijnen.wordpress.com/radioxray/) and was originally compiled for a different study focusing on the radio–X-ray luminosity plane of accreting neutron stars. To this sample, we added Z sources, two jet-quenched accreting neutron stars, and the accreting pulsars. The X-ray luminosities of the jet-quenched neutron stars have similar radio luminosities and the accreting pulsars have similar physical characteristics. We note that, as discussed extensively in the next section, it remains unclear whether the radio emission from these two classes of objects originates from a jet or an outflow.

The radio luminosities in the full sample were collected at 5 GHz, whereas we measured the 6-GHz radio luminosity of Sw J0243. Hence, we transformed the 5-GHz sample luminosities to 6-GHz ones by assuming a flat spectrum, which amounts to multiplying all luminosities in the sample by 6/5. The assumption of a flat radio spectrum is not accurate for all observations. For instance, a clear effect of the radio spectral shape on the position of black-hole systems on the radio–X-ray luminosity plane has recently been demonstrated. However, making this simplifying assumption is valid because we use the large sample only for a broad qualitative comparison between Sw J0243 and other types of source. Our conclusions—that Sw J0243 shows an apparent coupling between in- and outflow and is two orders of magnitude fainter than the Z sources—are not affected by assuming a flat radio spectrum.

Finally, we note that we plot the 0.5–10 keV X-ray luminosity of Sw J0243 to be consistent with the full sample. Before Sw J0243, no radio emission confirmed to be from a jet had been detected from any confirmed high-mass X-ray binary system containing a neutron star. Therefore, all neutron stars in the sample reside in low-mass X-ray binaries. While the 0.5–10 keV X-ray luminosity does not necessarily probe the same components of the accretion flow in low- and high-mass X-ray binaries, we plot this energy range to remain consistent between all sources and with the existing literature.

**Measuring the X-ray–radio correlation index.** We measured the correlation index from the 0.5–10 keV X-ray and 6-GHz radio luminosities in epochs 2–8 (that is, those with radio detections). We fit the following function to these seven data points:

\[
L_r = L_{x,\text{ref}} \frac{L_x}{L_{x,\text{ref}}}
\]

where \( L_{x,\text{ref}} \) is the average X-ray flux of all epochs and \( L_{x,\text{ref}} \) and \( \beta \) are free parameters. We find \( \beta = 0.54 \pm 0.16 \), which is consistent with the indices for both the black-hole and weakly magnetized neutron-star X-ray binaries.

It is important to treat this value with caution. Our monitoring result for Sw J0243 spans a factor of approximately 20 in X-ray luminosity and 5 in radio luminosity during the outburst. However, to accurately measure the coupling index between the radio and X-ray luminosities, detailed monitoring over at least two orders of magnitude in X-ray luminosity is strongly recommended. Therefore, although our result is consistent with other X-ray binaries, the exact value is not necessarily representative of the entire outburst or accreting pulsars in general.

From the \( L_x–L_r \) diagram, it is clear that without including the radio detection with the lowest X-ray luminosity, the correlation index distribution would be steeper. Although we cannot draw conclusions based on a single data point, this might reflect changes in the jet properties as the source becomes sub-Eddington and the accretion flow geometry changes.

**Alternative interpretations.** Here we briefly discuss a few alternative interpretations for the observed radio properties of Sw J0243. As mentioned in the main text, none of these alternative explanations can account for the observed combination of radio–X-ray coupling, flux levels, spectral index evolution and polarization properties.

First, the stellar wind in a high-mass X-ray binary system can emit in radio frequencies. Through a combination of optically thick and thin free–free processes, the radio spectrum of such a wind could be flat (that is, \( \alpha = 0 \)), as we observe in later epochs (see Fig. 1 and Extended Data Table 1). However, the systematic evolution seen in the spectral index, which is similar to that in low-mass X-ray binaries, is not expected for a stellar wind. The same goes for the clear coupling between radio and X-ray flux.

We can also consider the flux levels expected from a stellar wind. The typical flux, \( S_j \), of a stellar wind can be estimated \( 10^{29} \text{erg s}^{-1} \text{cm}^{-2} \) for a given mass-accretion rate \( M \), velocity \( v \), distance \( D \) and observing frequency \( \nu \):

\[
S_j = 7.26 \times 10^{29} \frac{M}{10 \text{M}_\odot \text{yr}^{-1}} \frac{v}{100 \text{km s}^{-1}} \frac{D}{1 \text{kpc}} \text{ mJy}
\]

where we ignore the electron temperature owing to its negligible effect on the predicted flux and assume a hydrogen wind (which yields the highest predicted flux). Conservatively assuming the escape velocity of a typical Be star as a minimum for the wind velocity, and using the lower limit of 5 kpc on the distance (which yields the highest flux density) at a frequency of 6 GHz, we find that the mass-loss rate in the wind needs to exceed \( 10^{-5} \text{M}_\odot \text{yr}^{-1} \) to account for the observed flux levels around the outburst peak. Such rates are only associated with Wolf–Rayet stars and are highly unlikely for a Be star, which are more likely to lose mass at a maximum rate of \( 10^{-4} \text{M}_\odot \text{yr}^{-1} \). At rates of \( 10^{-5} \text{M}_\odot \text{yr}^{-1} \), the wind flux would not be expected to exceed 0.01 \( \mu \text{Jy} \) —orders of magnitude below our radio detections.

Alternatively, accreting neutron stars could launch an outflow through the propeller mechanism. If the rotational velocity of the accreting material is lower than the neutron-star spin at the magnetospheric radius, the material can be expelled in a propeller outflow. However, making this simplifying assumption is valid because we use the large sample only for a broad qualitative comparison between Sw J0243 and other types of source. Our conclusions—that Sw J0243 shows an apparent coupling between in- and outflow and is two orders of magnitude fainter than the Z sources—are not affected by assuming a flat radio spectrum.
Radio pulsations at the neutron-star spin frequency also cannot be the origin of the observed emission. Although Sw J0243 is too faint to explicitly search for pulsations at the known spin, the spectral shape and evolution rule out this origin: radio pulsations have a steep ($\alpha \approx -1.4$) spectrum that does not evolve, in contrast to the different, evolving spectral shape observed in Sw J0243.

Coherent emission of any form is ruled out owing to the lack of observed circular polarization in Sw J0243 in any epoch.

Finally, shocks between the accreting material and the magnetosphere could give rise to radio emission. However, although the luminosity resulting from this mechanism could be expected to scale with the accretion rate, and thus the X-ray luminosity, we do not necessarily expect the shock spectrum to evolve as observed: the regular evolution of the spectrum from optically thin to thick, coupled to the decaying X-rays, implies that the same mechanism is responsible for all emission. The spectral shape towards the end of our radio monitoring (that is, flat) is inconsistent with the optically thin spectrum expected for the shocked emission.

Therefore, none of these alternative mechanisms can account for our radio observations of Sw J0243. The observed radio properties directly point towards a jet origin (as argued in the main text). Combined, the exclusion of alternatives and direct implication of a jet origin make Sw J0243 a completely distinct case from Her X-1 and GX 1+4. Although those strongly magnetized accreting neutron stars were recently detected in radio frequencies, these single-frequency and single-epoch detections could not directly imply a jet origin\(^{29}\). Several of the alternative mechanisms discussed above could also not be excluded. Therefore, although inspiring for our multi-band monitoring campaign of Sw J0243, those detections could neither convincingly prove the presence of jets in strongly magnetized neutron stars (thus disproving the existing theory) nor provide details on the properties of such jets.

**Code availability.** The code used to estimate the distance from the Gaia DR2 measurements is available at https://github.com/Alymantara/Sw_J0243. All data analysis software is publicly available for download (CASA: https://casa.nrao.edu; HEASoft: https://heasarc.nasa.gov/lheasoft/). This research used Astropy, a community-developed core Python package for Astronomy\(^{49}\), available at https://www.astropy.org.

**Data availability**

The VLA observations analysed in this work will become publicly available in the NRAO Science Data Archive (https://archive.nrao.edu/archive/adquery.jsp) on 8 November 2018 (first two epochs) and 20 February 2019 (remaining epochs), under project codes 17B-406 and 17B-420, respectively. However, prior access to the VLA observations will be granted by the corresponding author upon reasonable request. All Swift X-ray data are accessible in the HEASARC data archive. The radio–X-ray correlation data sample is available online at https://github.com/Alymantara/Sw_J0243. All data for the properties of such jets.

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Extended Data Fig. 1 | Marginal posterior distributions for the distance to Sw J0243. We show the distribution for an exponential and a uniform prior. The median value (50th percentile) of the distribution for the exponential prior is shown as the dot-dashed line. \( L \) is the scale parameter of the exponential prior and \( r_{\text{lim}} \) is the maximum distance in the uniform prior. PDF, probability density function.
### Extended Data Table 1 | Overview of VLA radio observations of Sw J0243

| Radio Epoch | Start (UTC)    | End (UTC)     | Observing frequencies | Leakage Calibrator | Beam size (position angle) |
|-------------|----------------|---------------|-----------------------|--------------------|----------------------------|
| 1           | 2017-10-10 05:37:00 | 2017-10-10 06:09:50 | 6 GHz, 22 GHz         | No                 | 1.12" x 0.74" (47.4 deg)  |
| 2           | 2017-11-08 00:46:52  | 2017-11-08 01:29:42 | 6 GHz                 | No                 | 2.13" x 1.12" (-80.0 deg) |
| 3           | 2017-11-15 03:21:21  | 2017-11-15 04:46:36 | 6 GHz, 22 GHz         | Yes                | 1.32" x 0.99" (35.3 deg)  |
| 4           | 2017-11-21 06:27:33  | 2017-11-21 07:52:46 | 6 GHz, 22 GHz         | Yes                | 1.42" x 0.97" (-30.9 deg) |
| 5           | 2017-11-22 23:29:24  | 2017-11-23 00:54:36 | 6 GHz, 22 GHz         | Yes                | 1.89" x 1.06" (-67.6 deg) |
| 6           | 2017-11-28 00:26:51  | 2017-11-28 01:58:04 | 6 GHz, 22 GHz         | Yes                | 1.54" x 1.02" (70.7 deg)  |
| 7           | 2017-12-02 05:47:30  | 2017-12-02 07:20:14 | 6 GHz, 22 GHz         | Yes                | 1.33" x 1.03" (-31.2 deg) |
| 8           | 2018-01-09 22:14:52  | 2018-01-09 22:57:44 | 6 GHz                 | No                 | 1.61" x 1.10" (76.9 deg)  |

For each radio epoch, we list the start and end time of the target observations in UTC (that is, not including the initial setup and calibration), the observing frequencies, whether we observed a leakage calibrator, and the beam size and position angle (in degrees east of north) at each frequency. The 6-GHz observations were performed with 4 GHz of bandwidth and the 22-GHz observations with 8 GHz of bandwidth.
### Extended Data Table 2 | VLA radio flux density, polarization and position measurements

| Radio Epoch | Observing frequency | Flux density [µJy] | Spectral index $\alpha$ | Linear polarization | 6 GHz position |
|-------------|---------------------|-------------------|-------------------------|---------------------|----------------|
| 1           | 6 GHz               | < 12.0            | -                       | -                   | -              |
|             | 22 GHz              | < 9.0             | -                       | -                   | -              |
| 2           | 6 GHz               | 77.1 ± 4.2        | -                       | -                   | RA: 02:43:40.440 ± 0.029s Dec: +61:26:03.73 ± 0.10" |
|             | 22 GHz              |                   | -                       | -                   |                |
| 3           | 6 GHz               | 92.6 ± 3.8        | -0.64 ± 0.16             | < 17%               | RA: 02:43:40.425 ± 0.022s Dec: +61:26:03.73 ± 0.18" |
|             | 22 GHz              | 40.3 ± 5.0        |                         |                     |                |
| 4           | 6 GHz               | 63.4 ± 4.3        | -0.62 ± 0.21             | < 27%               | RA: 02:43:40.419 ± 0.015s Dec: +61:26:03.80 ± 0.13" |
|             | 22 GHz              | 28.5 ± 5.6        |                         |                     |                |
| 5           | 6 GHz               | 55.3 ± 4.4        | -0.47 ± 0.27             | < 34%               | RA: 02:43:40.430 ± 0.026s Dec: +61:26:03.74 ± 0.10" |
|             | 22 GHz              | 30.0 ± 8.0        |                         |                     |                |
| 6           | 6 GHz               | 34.8 ± 4.0        | -0.12 ± 0.17             | < 47%               | RA: 02:43:440 ± 0.024s Dec: +61:26:03.65 ± 0.13" |
|             | 22 GHz              | 29.8 ± 5.2        |                         |                     |                |
| 7           | 6 GHz               | 24.7 ± 4.5        | 0.08 ± 0.21              | < 75%               | RA: 02:43:40.419 ± 0.028s Dec: +61:26:03.69 ± 0.23" |
|             | 22 GHz              | 27.5 ± 4.7        |                         |                     |                |
| 8           | 6 GHz               | 21.3 ± 4.0        | -                       | -                   | RA: 02:43:40.432 ± 0.042s Dec: +61:26:03.97 ± 0.21" |

For each radio epoch and observing frequency, we show the observed flux densities (or 3σ upper limits in case of non-detection), the spectral index when both 6- and 22-GHz observations were carried out, the most stringent upper limit on linear polarization per epoch, if available, and the 6-GHz position per epoch. All uncertainties are 1σ, while upper limits are quoted at 3σ. The errors on the position are calculated by taking the maximum of the synthesized beam size divided by the signal-to-noise ratio of the source detection and 10% of the synthesized beam size, following VLA guidelines.
Extended Data Table 3 | Swift-XRT flux measurements

| Radio Epoch | Swift XRT ObsId(s) | Start date(s) | Unabsorbed flux [10^{-4} erg s^{-1} cm^{-2}] | Interpolated flux [10^{-4} erg s^{-1} cm^{-2}] |
|-------------|--------------------|---------------|---------------------------------------------|---------------------------------------------|
| 1           | 10336007           | 2017-10-10    | 1.43 ± 0.01                                 | n/a                                         |
| 2           | 10336022           | 2017-11-09    | 36.9 ± 0.25                                 | n/a                                         |
| 3           | 10336025           | 2017-11-15    | 23.7 ± 0.16                                 | n/a                                         |
| 4           | 10336025 10336031 | 2017-11-15 2017-11-27 | 23.7 ± 0.16 10.5 ± 0.07 | 16.0 ± 0.11 14.2 ± 0.10 |
| 5           | 10336025 10336031 | 2017-11-15 2017-11-27 | 23.7 ± 0.16 10.5 ± 0.07 | 16.0 ± 0.11 14.2 ± 0.10 |
| 6           | 10336031           | 2017-11-27    | 10.5 ± 0.07                                 | n/a                                         |
| 7           | 10336033           | 2017-12-01    | 6.47 ± 0.04                                 | n/a                                         |
| 8           | 10467007 10467008 | 2018-01-02 2018-01-13 | 2.04 ± 0.01 1.47 ± 0.01 | 1.64 ± 0.01 1.64 ± 0.01 |

For each radio epoch, we list the Swift-XRT observations used to determine the unabsorbed X-ray flux. When two observations (ObsIds) are listed, the X-ray flux estimate for that radio epoch was determined through log-linear interpolation between the two observations. Three leading zeros have been removed from all ObsIds. All errors are quoted at 1\(\sigma\).
Extended Data Table 4 | Swift-XRT spectral fit parameters

| Swift XRT Obsid | \( N_H \) \(10^{22} \) cm\(^{-2}\) | \( T_{BB} \) [keV] | \( N_{BB} \) | \( \Gamma \) | \( N_\text{PO} \) [phot/keV/cm\(^2\)/s] | \( \chi^2 / \nu \) |
|----------------|----------------------|-----------------|-----------|------|-----------------|--------|
| 10336007       | 1.60 ± 0.10          | 1.94 ± 0.06     | 43 ± 8    | 1.96 ± 0.16 | 1.85 ± 0.26 | 1028.8 / 865 |
| 10336022       | 1.19 ± 0.08          | 2.08 ± 0.06     | 1036 ± 162 | 1.84 ± 0.15 | 39.2 ± 4.6  | 814.3 / 877  |
| 10336025       | 1.28 ± 0.08          | 1.96 ± 0.05     | 810 ± 104 | 1.99 ± 0.14 | 28.7 ± 3.2  | 967.5 / 874  |
| 10336031       | 1.57 ± 0.09          | 1.96 ± 0.04     | 387 ± 46  | 2.13 ± 0.16 | 13.3 ± 1.7  | 944.6 / 873  |
| 10336033       | 1.46 ± 0.07          | 1.96 ± 0.04     | 212 ± 24  | 1.77 ± 0.13 | 6.56 ± 0.65 | 1007.4 / 889 |
| 10467007       | 1.47 ± 0.08          | 1.75 ± 0.06     | 80 ± 10   | 1.81 ± 0.13 | 2.42 ± 0.25 | 930.4 / 876  |
| 10467008       | 1.42 ± 0.04          | -               | -         | 1.31 ± 0.02 | 1.48 ± 0.04 | 1058.2 / 870 |

For each analysed Swift-XRT observation, we list the best-fit spectral parameters for a TBABS\(^{*}\)*(BBODYRAD + POWERLAW) model in XSPEC. \( N_H \) is the neutral hydrogen density, \( T_{BB} \) and \( N_{BB} \) are the blackbody temperature and normalization, respectively, and \( \Gamma \) and \( N_\text{PO} \) are the power-law index and normalization, correspondingly. The final column lists the \( \chi^2 \) divided by the number of degrees of freedom, \( \nu \). As in Be/X-ray binaries, local absorption can contribute to the total absorption column and we do not tie \( N_H \) between observations. In observation 10467008, the inclusion of a blackbody spectral component was not statistically required. All errors are quoted at 1\( \sigma \).