Baryons in the relativistic jets of the stellar-mass black-hole candidate 4U 1630–47

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Accreting black holes are known to power relativistic jets, both in stellar-mass binary systems and at the centres of galaxies. The power carried away by the jets, and, hence, the feedback they provide to their surroundings, depends strongly on their composition. Jets containing a baryonic component should carry significantly more energy than electron–positron jets. Energetic considerations and circular-polarization measurements have provided conflicting circumstantial evidence for the presence or absence of baryons in jets, and the only system in which they have been unequivocally detected is the peculiar X-ray binary SS 433 (refs 4, 5). Here we report the detection of Doppler-shifted X-ray emission lines from a more typical black-hole candidate X-ray binary, 4U 1630–47, coincident with the reappearance of radio emission from the jets of the source. We argue that these lines arise from baryonic matter in a jet travelling at approximately two-thirds the speed of light, thereby establishing the presence of baryons in the jet. Such baryonic jets are more likely to be powered by the accretion disk than by the spin of the black hole, and if the baryons can be accelerated to relativistic speeds, the jets should be strong sources of γ-rays and neutrino emission.

As part of a campaign to study the connection between relativistic jets and disk winds in X-ray binaries, we used the European Space Agency’s XMM-Newton spacecraft and the Australia Telescope Compact Array (ATCA) to make two quasi-simultaneous observations (spaced by less than two days) of the stellar-mass black-hole candidate X-ray binary 4U 1630–47 during its 2012 outburst (Extended Data Table 1). The first X-ray observation, on September 12–12, showed an X-ray spectrum fully consistent with emission from a standard accretion disk. The quasi-simultaneous radio observation did not detect the source down to 3σ limits on the specific intensity of 68 μJy per beam solid angle (angular-resolution element), in images obtained at both 5.5 and 9.0 GHz. In the second observation, on September 28, an additional component was required to model the X-ray spectrum: a non-thermal power law, thermal bremsstrahlung or a Comptonization component (Extended Data Table 2). Further, three narrow X-ray emission lines were significantly detected at energies of 4.04, 7.28 and 8.14 keV (Fig. 1). The quasi-simultaneous ATCA observations detected a radio source at levels of 110 ± 17 and 66 ± 28 μJy per beam at 5.5 and 9.0 GHz, respectively.

The strongest emission line, at 7.28 keV, is narrow, with a width of 0.17 ± 0.05 keV. There are no known lines with this rest energy and the most plausible explanation is that this is blueshifted emission from highly-ionized Fe. However, the narrow linewidth, strong blueshift and the lack of an extended red wing (excess emission at long wavelength) in the line profile (which would have indicated relativistic effects) argue against a disk reflection line similar to those previously observed in both X-ray binaries and active galactic nuclei. Although narrow emission lines are frequently observed from the corona in very high-inclination X-ray binaries (the so-called accretion disk corona sources), they are not significantly blueshifted (Supplementary Information). Given the reactivation of the jets implied by the onset of radio emission, we are left with the intriguing possibility that the 7.28-keV emission line arises from a relativistic jet moving towards the observer.

Taken in isolation, this would constrain the jet velocity to be >0.3c, where c is the speed of light, and the inclination angle to be <73° relative to the line of sight, assuming Fe XXVI Kα emission (>0.4c and <66°, respectively, for Fe XXV Kα emission). However, if the 4.04-keV line is associated with the corresponding redshifted Fe XXVI Kα emission from the receding jet, we can uniquely constrain the jet velocity to be 0.66c and the inclination angle of the jet axis relative to the line of sight to be 65° (0.63c and 63°, respectively, for Fe XXV Kα emission). Given that the disk normal is constrained, by the observed X-ray dips and the absence of eclipses, to be in the range 60–75° relative to the line of sight, and assuming that the outer and inner disks have the same inclination (that is, there is no warp), this suggests that the jets are aligned with the disk normal, and are hence perpendicular to the disk plane. Furthermore, by assuming identical blueshifts for the 7.28- and 8.14-keV lines, we find a unique identification of such lines as Fe XXVI and Ni XXVII and can self-consistently fit the observed emission lines and the hard continuum component as an emission spectrum from hot, diffuse, Doppler-shifted gas at a temperature of 21 ± 4 keV (energy and temperature being linearly related by Boltzmann’s constant), which contributes 19% of the total unabsorbed flux in the 2–10 keV band (Fig. 2).

Fitting a standard multicolour disk and power law with a photon index of 2 = 2 to model the continuum flux in the second observation gave a bolometric flux in excess of 5.2 × 10−8 erg cm−2 s−1. However, the exact value depends significantly on the relatively poorly constrained photon index. For a photon index of 2 = 2 the power-law component comprised 50% of the total bolometric luminosity, whereas for 2 = 2.5 the power-law contribution was as high as 90%. In either case, this implies that the source was in the ‘anomalous’ accretion state, characterized by a luminosity in excess of 2.5 × 1038 erg s−1 with a dominant contribution to the spectrum from a steep power-law component. The accretion flow is believed to consist of a standard disk, but with a hot corona responsible for Compton upscattering a significant fraction of the disk photons (that is, the photons gain energy after inelastic scattering with energetic electrons in the corona). The only previous detection of jets from 4U 1630–47 also occurred while it was in an ‘anomalous’ state, when highly polarized, optically thin radio emission was detected, although no high-resolution X-ray spectra from that outburst are available to search for Doppler-shifted line emission. Contrasting the accretion flow geometry with that of the standard soft state in which jets are produced, we can self-consistently fit the observed emission lines and the hard continuum component as an emission spectrum from hot, diffuse, Doppler-shifted gas at a temperature of 21 ± 4 keV (energy and temperature being linearly related by Boltzmann’s constant), which contributes 19% of the total unabsorbed flux in the 2–10 keV band (Fig. 2).

Narrow, Doppler-shifted X-ray emission lines have previously been reported during an ‘apparent standard’, slim disk state of 4U 1630–47 observed by NASA’s Rossi X-Ray Timing Explorer. However, the poorer spectral resolution of that spacecraft relative to XMM-Newton prevented the definitive association of these lines with either the accretion disk or the jet. Although we find that interpreting these lines as red-
blueshifted Fe XXVI Kα emission from a bipolar jet would give a consistent inclination angle of 58–67° and a slightly lower jet speed of 0.3c–0.4c, the spectral resolution is insufficient to draw more concrete conclusions. Therefore, until now, the only X-ray binary for which there was unambiguous evidence for baryons in the jets was SS 433, in which Doppler-shifted emission lines are seen in both the optical and X-ray bands. However, its persistent, supercritical accretion rate makes it extremely difficult, even if one knew the true jet velocity and inclination angle, and, hence, the expected redshifts. The observed emission lines in 4U 1630-47 could then arise from the particular characteristics of the jets during the poorly studied ‘anomalous’, high-luminosity state in which they were observed.

Most previous attempts to constrain jet composition in both X-ray binaries and active galactic nuclei have relied on energetics considerations, because baryon-loaded jets can carry significant kinetic power away from the compact central objects without radiating. In some active galactic nuclei, the detection of circular polarization has been used to determine the low-energy electron population, and hence to claim, on energetic grounds, that a significant baryonic component can be ruled out. However, the few reported circular-polarization detections in X-ray binaries were unable to place strong constraints on the jet composition.

components of Fe XXVI ranges from 1.9 ± 1.1 to 2.1 ± 1.3 (Extended Data Table 3), consistent with 3.2, the ratio predicted for Doppler boosting in a continuous jet. Assuming that the lines are Doppler-broadened by divergence in a conical outflow, we use their widths to determine an upper limit to the opening angle of the jet of 3.7°–4.5°.

4U 1630-47 is a recurrent transient system. The X-ray spectral and timing features observed during its many well-studied outbursts are typical of other low-mass X-ray binaries, and, together with the absence of type I X-ray bursts, make it one of the best candidates to contain a black hole. However, the high column density in the direction of the system has precluded spectroscopic classification of the detected infrared counterpart, and a dynamical mass estimate is still lacking. The donor star is most likely to be a relatively early-type (late B or F class) star, typically of other low-mass X-ray binaries.

Figure 1 | Residuals from the continuum modelling of the X-ray spectra. Ratio of data (90% error bars) to results of continuum model for the first (a, XMM1) and second (b, XMM2) XMM-Newton observations. The dotted vertical lines indicate the rest energy of the transitions of Fe XXVI (6.97 keV) and Ni XXVII (7.74 keV). The flux ratio between the blue- and redshifted Fe XXVI Kα emission from a bipolar jet would give a consistent inclination angle of 58–67° and a slightly lower jet speed of 0.3c–0.4c, the spectral resolution is insufficient to draw more concrete conclusions. Therefore, until now, the only X-ray binary for which there was unambiguous evidence for baryons in the jets was SS 433, in which Doppler-shifted emission lines are seen in both the optical and X-ray bands. However, its persistent, supercritical accretion rate makes it extremely difficult, even if one knew the true jet velocity and inclination angle, and, hence, the expected redshifts. The observed emission lines in 4U 1630-47 could then arise from the particular characteristics of the jets during the poorly studied ‘anomalous’, high-luminosity state in which they were observed.

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Figure 2 | X-ray observations of 4U 1630-47. a, MAXI/All-Sky Monitor light curve of 4U 1630-47 (MJD, modified Julian date). The times of the XMM-Newton and ATCA observations reported here are indicated with red and blue dashed lines, respectively (Extended Data Table 1). b–d, 2–10 keV unfolded X-ray spectra (flux multiplied by squared energy, shown as a function of energy; error bars (90%) are too small to see). The first observation can be fully described by a standard disk (b). As the source brightens to more than 2.5 × 10^38 erg s^-1 in the 2–10 keV band, the spectrum requires an additional hard, power-law, component (black dot–dash line) and three narrow emission lines (red and blue dot–dash lines) (c). Alternatively, two thermal plasma components (bvapec in XSPEC) with a temperature of 21 keV (red and blue dot-dashed lines) can account self-consistently for both the hard component and the narrow emission lines (d). Model information refers to XSPEC components.
Arguments based on pressure balance and minimum-energy calculations in the lobes of radio galaxies have suggested that cold protons may carry the bulk of the kinetic energy, but there are caveats to these interpretations and uncertainty in the jet composition remains. In the best-constrained X-ray binary system, caloriometry of the jet-blown bubble around Cygnus X-1 suggested that the jets should carry a significant cold proton component, although alternative explanations were possible. The detection of baryons in the jets of 4U 1630–47 has finally confirmed this picture, at least for certain accretion states.

If they can be accelerated to mildly relativistic speeds, the presence of baryons in an X-ray binary jet suggests that γ-rays could be produced in collisions with high-energy photons or with protons in the stellar wind of the companion star. Such hadronic mechanisms are in principle capable of explaining the observed γ-ray flux from the microquasar Cygnus X-3, although leptonic models seem equally viable. Even for low-mass X-ray binaries with no strong stellar wind, hadronic models suggest that the presence of relativistic baryons would give rise to γ-ray emission that could be detected by Fermi-LAT, MAGIC II and the CTA. In that case, the hadronic mechanism should also generate an intense flux of neutrinos. Thus, baryonic jets also have important implications for current and future neutrino telescopes, and our results suggest that high-luminosity outbursts could provide the best opportunities for neutrino detection.

Finally, the jet composition should be affected by the physical mechanism responsible for launching the jets. Jets powered by an accretion disc are expected to contain baryons, whereas in the absence of entrainment (as is probably the case in the absence of a strong stellar wind), jets powered by black-hole spin are more likely to produce purely leptonic jets with significantly higher Lorentz factors. Although there are claims that transient jets from X-ray binaries are powered by black-hole spin, this work remains controversial, and so additional evidence detailing the jet composition can provide independent constraints on the jet-launching mechanism.

**METHODS SUMMARY**

The X-ray observations were made with XMM-Newton, using the EPIC pn charge-coupled-device camera in burst mode. Data were reduced using the XMM-Newton Science Analysis Software. We corrected for a rate-dependent charge transfer inefficiency and rebinned the data, but did not perform background subtraction, owing to the source brightness and the lack of source-free background regions in burst mode. The resulting X-ray spectra were fitted using the spectral analysis package XSPEC. Whereas the spectrum from 2012 September 11 could be well fitted with a standard disk model, that from September 28 required an additional hard component (Extended Data Table 2). After the spectral continuum had been modelled, a strong, narrow emission feature remained in the residuals of the observation of September 28, at an energy of ~7.3 keV. Additional, weaker features were detected at ~4.1 and ~8.2 keV, whose high statistical significance was confirmed both by F-test and by Monte Carlo simulations. We also verified the lines to be unabsorbed against systematic shifts of up to 2% in the energy scale (although the model became degenerate if the line energy was shifted to coincide with the neutral Fe edge). The best-fitting model parameters are given in Extended Data Table 3.

Quasi-simultaneous radio observations were made with ATCA in its compact H214 configuration, using the Compact Array Broadband Backend to observe simultaneously at 5.5 and 9.0 GHz. Data were initially imported into MRIRAD, and further processed within the Common Astronomy Software Application, using standard procedures. PKS B1934–638 was used as the amplitude and band-pass calibrator, and PMN J1603–4904 was used as the secondary calibrator. No radio emission was detected on 2012 September 10, with an upper limit of three times the rms squared noise level. The steep-spectrum emission seen on September 29 was fitted with an elliptical Gaussian in the image plane.

**Full Methods** and any associated references are available in the online version of the paper.

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Supplementary Information is available in the online version of the paper.
METHODS

XMM-Newton. In this section, we provide additional information about the analysis of the XMM-Newton observations of 4U 1630–47. A summary of the observations is shown in Extended Data Table 1. Owing to the high count rate from the source, $\approx 10^4$ counts s$^{-1}$, we used the EPIC pn charge-coupled-device (CCD) camera in burst mode, in which only one CCD chip is operated and the data are collapsed into a one-dimensional row (4.4$^3$) and read out at high speed, the second dimension being replaced by timing information, and applied the Science Analysis Software task epfast to the event files to correct for a charge transfer inefficiency effect that has been observed in this mode when high count rates are present$^{14}$. We did not use the EPIC MOS CCD cameras during the observations, to avoid telemetry overflows. Data products were reduced using the Science Analysis Software version 12.0.1. We re-binned the EPIC pn spectra to oversample the full-width at half-maximum of the energy resolution by a factor of three and to have a minimum of 25 counts per bin, to allow the use of the $\chi^2$ statistic. To account for systematic effects, we added a 0.8% uncertainty to each spectral bin after re-binning. We used the pn spectra between 2 and 10 keV.

In the EPIC pn burst mode, there are no source-free background regions, because the point spread function of the telescope extends farther than the central CCD boundaries$^{10,11}$. Because 4U 1630–47 is very bright, its spectrum will not be significantly modified by the ‘real’ background, which contributes less than 1% to the total count rate at most of the energy band. Conversely, subtracting the background extracted from the outer columns of the central CCD will modify the source spectrum, because the point spread function is energy dependent and the source photons scattered to the outer columns do not show the same energy dependence as the photons focused on the inner columns. Therefore, we checked the effect of subtracting the ‘background’ extracted from the outer regions of the central CCD on the parameters of the lines. Having established that this resulted in no significant changes to the lines, we chose not to subtract such a background when making the final fits, to provide the best possible measurement of the true source spectrum.

We fitted the XMM-Newton data using the spectral analysis package XSPEC$^{16}$, testing standard X-ray binary models for single-disk emission (diskbb in XSPEC), power-law emission (po in XSPEC), bremsstrahlung (bremss in XSPEC), thermal Comptonization (compss in XSPEC), disk emission plus power-law (diskbb+po), disk emission plus bremsstrahlung (diskbb+bremss) and disk emission plus thermal Comptonization (diskbb+compt). In each case, we included a neutral absorber (tbabs in XSPEC) to account for interstellar absorption along the line of sight. We also included a narrow emission feature at 2.28 keV to account for residual calibration uncertainties at the gold edge of the pn camera$^{12}$.

We found that the first observation could be well fitted by a standard disk (reduced-$\chi^2$ = 0.97 for 128 degrees of freedom (d.o.f.)). In contrast, for the second observation, either a one-component thermal Comptonization model or a two-component model was required to obtain an acceptable fit (reduced-$\chi^2$ $\geq$ 2). A summary of the models tested and the corresponding quality of the fits is shown in Extended Data Table 2. The main difference between the first and second observations is the appearance of a hard component in the latter observation in addition to the thermal disk component. Further support for the existence of this component is given by the increase in the hard-X-ray flux ($$\geq$$10 keV) between the first and second observations, as detected by MAXI/All-Sky Monitor and Swift/BAT. In particular, the Swift/BAT 15–50 keV count rate increased from 0.019 $\pm$ 0.001 counts cm$^{-2}$ s$^{-1}$ to 0.036 $\pm$ 0.002 counts cm$^{-2}$ s$^{-1}$. However, we cannot discriminate between the three components (power law, bremsstrahlung or thermal Comptonization) used to model the additional emission in the second observation, owing to the low effective area of XMM-Newton at energies $>10$ keV, at which such a component should become dominant. We found that a one-component thermal Comptonization model with low seed photon and plasma temperatures ($$$\sim$$0.7$ keV and 1.9$^\circ$ K, respectively) and a high optical depth ($\tau = 8$) could fit the second observation just as well as the two-component model. However, the 15–50 keV flux predicted by the one-component model, $3 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$, is lower than the flux detected by Swift/BAT, $2 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$, by almost one order of magnitude. In contrast, the two-component models predict a 15–50 keV flux of $$(2\pm3) \times 10^{-9}$$ erg cm$^{-2}$ s$^{-1}$, in excellent agreement with Swift/BAT.

Therefore, we discard the one-component thermal Comptonization model for the rest of this work, but include it for completeness in Extended Data Tables 2 and 3, together with all the other tested models.

Having modelled the continuum emission, a strong, narrow emission feature remained in the residuals of the second observation at $7.28$ keV, with additional weaker features at energies of $3.5$, $7.8$ and $10$ keV. The emission of a narrow Gaussian at $7.28$ keV, to account for the most significant feature, improved the fit from $\chi^2 = 1.70$ (127 d.o.f.) to 1.07 (124 d.o.f.). The probability of such an improvement occurring by chance, as indicated by an $F$-test, is $5 \times 10^{-17}$. We also tested the significance of the weaker features, including them one by one in addition to the feature at 7.28 keV. Because the weak features are narrow, we coupled their widths to that of the 7.28-keV feature to prevent an arbitrary increase in the linewidths from absorbing deficiencies in the continuum model. We found that independently including the $4.1$-keV and $8.2$-keV features improved the quality of the fit to $\chi^2 = 0.97$ (122 d.o.f.) and 0.95 (122 d.o.f.), respectively (a $F$-test indicated that the probabilities of such improvements occurring by chance were 0.0007 and 0.0002, respectively). For the feature at 3.5 keV, the chance probability of the fit improvement as given by the $F$-test was 0.023. The feature at 7.8 keV is weaker than that at 8.2 keV, and unless the energy was fixed, the fit shifted the energy to 8.2 keV. If the feature at 7.8 keV was included in addition to the 8.2-keV feature, the chance probability of the fit improvement as given by the $F$-test was 0.041.

Because there are caveats to the use of the $F$-test to study the presence of emission lines over a continuum$^{17}$, we also performed Monte Carlo simulations to confirm the significance of the 4.1-keV and 8.2-keV features. As an example, we took the best-fitting parameters of the model consisting of absorbed disk emission plus thermal Comptonization (diskbb + comptt; Extended Data Table 3) and the 7.28-keV Gaussian emission line as our null hypothesis. We then tested the chance probability of any extra emission line against the null hypothesis.

For this, we fitted the data with the null-hypothesis model and simulated a spectrum with the same exposure time as the data. We fitted the simulated spectrum with the model used to construct it, providing a refined null-hypothesis model that differed from the previous one only in photons statistics. We then added to the model a Gaussian emission line, varying its energy from 3.0 to 9.0 keV in steps of 0.2 keV. We chose the linewidth to be equal to the one that we found in our best-fit model of the data with the three Gaussian emission lines, $\sigma = 0.17 \pm 0.05$ keV, and we allowed the normalization to vary. For each spectrum, we recorded the best-fitting parameters and the maximum $\Delta \chi^2$ among the lines. We then repeated the above steps 1,000 times and obtained the distribution of maximum $\Delta \chi^2$ to be compared with the result obtained from the data. The addition of an extra Gaussian to the data at 4.1 or 8.2 keV improved the fit by $\Delta \chi^2 = 12.73$ or 13.77, respectively, compared with the null hypothesis.

Only six and, respectively, one of the 1,000 simulated spectra showed a maximum $\Delta \chi^2$ equal to or higher than those found by fitting the data with the additional 4.1- and 8.2-keV lines. Therefore, these additional lines are significant at levels of 99.4% and 99.9%, respectively.

In summary, given the higher significance of the $\sim 4.1$- and $8.2$-keV features, we consider it likely that they are real and we discard the other weak features, which have significantly higher chance probabilities. In Extended Data Table 3, we show the parameters of the best-fit models. The lines are robust against significance tests, and we also tested whether they are robust against possible systematic errors in the energy scale. For this, we shifted the energy scale by as much as $\pm 2\%$ in the event files of both observations and re-extracted spectra and response matrices. Coincidentally, the maximum possible systematic error of $\sim 2\%$ in the energy scale would shift the photons of the line at 7.28 keV to the energy of the neutral Fe edge, causing model degeneracy. Therefore, we encourage future exposures with high-resolution gratings to mitigate against possible systematics and definitively confirm the exact energies of the lines.

Finally, we searched for line variability within the second observation by dividing the events file into two, and extracted four different parts and extracting and fitting the corresponding spectra. We did not detect any significant variation of the lines among the different intervals. However, owing to the poor statistics we obtain large errors and cannot exclude variability with high significance. Longer exposures with high-resolution gratings would be required to address definitively the existence of line variability, as might be expected in the case of jet precession.

Australia Telescope Compact Array. ATCA was used to observe 4U 1630–47 at two epochs, as detailed in Extended Data Table 1. We made simultaneous observations at 5.5 and 9.0 GHz using the Compact Array Broadband Backend system$^{18}$. We observed with 2,048 MHz of contiguous bandwidth in each of the two frequencies, split into four different parts and extracting and fitting the corresponding spectra. We did not detect any significant variation of the lines among the different intervals. However, owing to the poor statistics we obtain large errors and cannot exclude variability with high significance. Longer exposures with high-resolution gratings would be required to address definitively the existence of line variability, as might be expected in the case of jet precession.

Data were imported into MIRIAD$^{19}$, and immediately written out to FITS format for further processing within the Common Astronomy Software Application$^{20}$. We edited out narrowband radio-frequency interference, before deriving the external gain calibration, using PKS B1934–638 as the band-pass calibrator and to set the amplitude scale. We used PMN J1603–4904 to derive the amplitude and phase gains that were subsequently applied to the target field. To filter out the diffuse emission in the field and enhance the sensitivity to point sources, we only used the images obtained above 2.5$\sigma$ using the radio images. We used natural weighting to maximize the image sensitivity. The source was too faint for self-calibration. On 2012 September 10, the source was not detected at either frequency, and we estimated the 3$\sigma$ upper limit on its flux density as three times the root mean square noise in the image. On 2012 September 29, when the source was significantly

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detected, we measured its flux density by fitting an elliptical Gaussian to the source in the image plane.

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## Extended Data Table 1 | Observation log

| Observation | Observation ID | Observation Times (UTC) |
|-------------|----------------|-------------------------|
|             |                | (day.month.year hr:min) |
| XMM1        | 0670673101     | 11.09.2012 20:14 - 12.09.2012 05:39 |
| ATCA1       | C2514          | 10.09.2012 01:08 - 10.09.2012 09:03 |
| XMM2        | 0670673201     | 28.09.2012 06:33 - 28.09.2012 21:50 |
| ATCA2       | C2514          | 29.09.2012 02:36 - 29.09.2012 09:58 |
Extended Data Table 2 | Quality of the spectral fits ($\chi^2$) to the XMM-Newton observations, using different continuum models

| Model                  | $\chi^2$ (d.o.f.) | XMM1 | XMM2 |
|------------------------|-------------------|------|------|
| tbabs diskbb           | 0.97 (128)        | 2.12 (128) |
| tbabs po               | 9.44 (128)        | 12.9 (128)  |
| tbabs bremsss          | 2.59 (128)        | 3.26 (128)  |
| tbabs comptt           | 0.87 (126)        | 1.26 (126)  |
| tbabs (diskbb + po)    | 0.95 (127)        | 1.70 (127)  |
| tbabs (diskbb + bremsss) | 0.96 (126) | 1.70 (126)  |
| tbabs (diskbb + comptt) | 0.95 (127) | 1.67 (127)  |
Extended Data Table 3 | Parameters for each of the best-fit models to the 2–10-keV EPIC pn spectra from the XMM-Newton observations

| Obs.   | $N_{\text{Habs}}$ | $kT_{\text{dbb}}$ (keV) | $k_{\text{dbb}}$ | $kT_b$ (keV) | $k_{\text{b}}$ | $\tau$ | $k_{\text{comptt}}$ | $E_{\text{gau}}$ (keV) | $\sigma$ (keV) | Flux$_{\text{gau}}$ | $E_{\text{cm}}$ (eV) | $E_{\text{cm}}$ (eV) | $E_{\text{cm}}$ (eV) |
|--------|-----------------|------------------|----------------|--------------|-------------|--------|-----------------|------------------|--------------|----------------|----------------|----------------|----------------|
| XMM1   | $8.34 \pm 0.08$ | $1.82 \pm 0.01$  | $107 \pm 3$     | --           | --          | --     | --              | --               | --           | --             | --             | --             | --             |

| XMM1   | $7.5 \pm 0.4$   | $0.69 \pm 0.08$  | --              | --           | --          | --     | --              | --               | --           | --             | --             | --             | --             |
| XMM2   | $7.36 \pm 0.09$ | $0.72 \pm 0.05$  | $1.86 \pm 0.04$ | $3.23 \pm 0.09$ | $4.06 \pm 0.07$ | $1.9 \pm 1.0$ | $5 \pm 2$ | $0.79 \pm 0.11$ | $7.24 \pm 0.03$ | $0.11 \pm 0.03$ | $3.8 \pm 0.8$ | $23 \pm 4$ | $0.9 \pm 0.7$ | $7 \pm 4$ |

| Obs.   | $N_{\text{Habs}}$ | $kT_{\text{dbb}}$ (keV) | $k_{\text{dbb}}$ | $kT_e$ (keV) | $Z_{\text{blue}}$ | $Z_{\text{red}}$ | $Z_{\text{blue}}$ | $Z_{\text{red}}$ | $Z_{\text{blue}}$ | $Z_{\text{red}}$ | $Z_{\text{blue}}$ | $Z_{\text{red}}$ | $Z_{\text{blue}}$ | $Z_{\text{red}}$ |
|--------|-----------------|------------------|----------------|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| XMM1   | $8.5 \pm 0.2$   | $1.78 \pm 0.03$  | $113 \pm 6$    | $2 (f)$     | $\Gamma$     | $k_{\text{gpo}}$ | $E_{\text{gau}}$ (keV) | $\sigma$ (keV) | Flux$_{\text{gau}}$ | $E_{\text{cm}}$ (eV) | $E_{\text{cm}}$ (eV) | $E_{\text{cm}}$ (eV) |
| XMM2   | $8.6 \pm 0.1$   | $1.77 \pm 0.03$  | $123 \pm 7$    | $2 (f)$     | $1.7 \pm 0.3$  | $4.04 \pm 0.10$ | $3.0 \pm 1.4$ | $8 \pm 4$ | $0.87 \pm 0.19$ | $7.28 \pm 0.04$ | $0.17 \pm 0.05$ | $6.2 \pm 1.0$ | $37 \pm 9$ | $2.5 \pm 1.0$ | $18 \pm 10$ |

| Obs.   | $N_{\text{Habs}}$ | $kT_{\text{dbb}}$ (keV) | $k_{\text{dbb}}$ | $kT_e$ (keV) | $k_{\text{b}}$ | $k_{\text{b}}$ | $E_{\text{gau}}$ (keV) | $\sigma$ (keV) | Flux$_{\text{gau}}$ | $E_{\text{cm}}$ (eV) | $E_{\text{cm}}$ (eV) | $E_{\text{cm}}$ (eV) |
|--------|-----------------|------------------|----------------|--------------|-------------|-------------|------------------|--------------|----------------|----------------|----------------|----------------|
| XMM1   | $8.6 \pm 0.4$   | $1.79 \pm 0.06$  | $102 \pm 16$   | $1.2$        | $0.9 \pm 1.8$ | $0.8$       | $4.04 \pm 0.10$ | $3.2 \pm 1.3$ | $8 \pm 4$ | $0.87 \pm 0.19$ | $7.27 \pm 0.04$ | $0.17 \pm 0.05$ | $6.1 \pm 0.9$ | $37 \pm 8$ | $2.3 \pm 0.9$ | $18 \pm 10$ |
| XMM2   | $8.4 \pm 0.4$   | $1.74 \pm 0.05$  | $134 \pm 15$   | $5.3$        | $1.1 \pm 1.7$ | $0.05$     | $8.15 \pm 0.15$ | $2.9 \pm 1.4$ | $8 \pm 4$ | $0.88 \pm 0.18$ | $7.26 \pm 0.06$ | $0.17 \pm 0.05$ | $6.0 \pm 1.0$ | $37 \pm 8$ | $2.4 \pm 1.0$ | $19 \pm 11$ |

Uncertainties are quoted at the 90% level. $N_{\text{Habs}}$ is the column density of the neutral absorber in units of $10^{22}$ cm$^{-2}$. $k_{\text{dbb}}, k_{\text{po}}$, $k_{\text{brems}}$ and $k_{\text{comptt}}$ are the normalizations of the disk black-body, power-law, bremsstrahlung and Comptonization components in XSPEC units. $kT_{\text{dbb}}$ and $kT_{\text{comptt}}$ are the temperatures of the disk black-body and Comptonization components in units of keV. For the comptt component, we imposed a lower limit on the temperature of the plasma of 50 keV and an upper limit on the opacity of 2, and coupled the temperature of the seed photons to the temperature of the disk black body in the two-component model. The photon index of the power law, $\Gamma$, has been fixed to 2, because it is poorly constrained. $k_{\text{b}}$ and $k_{\text{b}}$ respectively represent the normalizations of the blue and red bvapec components in XSPEC units. $Z_{\text{blue}}$ and $Z_{\text{red}}$ respectively represent the velocity shifts for the blue and red bvapec components. 'Ni' represents the nickel abundance with respect to solar abundances; $v$ represents the velocity broadening for the bvapec components, for which we imposed the same value for the red and blue components. $E_{\text{gau}}$, $\sigma$, EW and Flux$_{\text{gau}}$ respectively represent the energy (in units of keV), width (in units of keV), equivalent width (in units of eV) and 2–10-keV unabsorbed flux (in units of $10^{-11}$ erg cm$^{-2}$ s$^{-1}$) of the Gaussian features. The width, $v$, was tied for all the emission lines during the fit. ‘p’ indicates that a parameter was pegged at its lower or upper limit.