Resolved atomic lines reveal outflows in two ultraluminous X-ray sources

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Ultraluminous X-ray sources are extragalactic, off-nucleus, point sources in galaxies, and have X-ray luminosities in excess of $3 \times 10^{39}$ ergs per second. They are thought to be powered by accretion onto a compact object. Possible explanations include accretion onto neutron stars with strong magnetic fields1, onto stellar-mass black holes (of up to 20 solar masses) at or in excess of the classical Eddington limit2-4, or onto intermediate-mass black holes (10$^3$-10$^5$ solar masses)5. The lack of sufficient energy resolution in previous analyses has prevented an unambiguous identification of any emission or absorption lines in the X-ray band, thereby precluding a detailed analysis of the accretion flow6-8. Here we report the presence of X-ray emission lines arising from highly ionized iron, oxygen and neon with a cumulative significance in excess of five standard deviations, together with blueshifted (about 0.2 times light velocity) absorption lines of similar significance, in the high-resolution X-ray spectra of the ultraluminous X-ray sources NGC 1313 X-1 and NGC 5408 X-1. The blueshifted absorption lines must occur in a fast-outflowing gas, whereas the emission lines originate in slow-moving gas around the source. We conclude that the compact object in each source is surrounded by powerful winds with an outflow velocity of about 0.2 times that of light, as predicted by models of accreting supermassive black holes and hyper-accreting stellar-mass black holes9,10.

NGC 1313 X-1, NGC 5408 X-1 and NGC 6946 X-1 are three ultraluminous X-ray sources (ULXs), with X-ray luminosities up to $\sim 10^{40}$ ergs s$^{-1}$. All three sources have been observed in spectral 'states' in which a large proportion of the flux emerges at energies below 2 keV (refs 6, 11) and in these states they show strong spectral deviations (0.6-1.2 keV) from the underlying continuum in charge-coupled device (CCD) spectra8,12. Owing to their relative proximity to Earth (distances $D < 7$ Mpc) and brightness, data quality is high, making them ideal targets for understanding the spectral residuals through powerful means to understand ULXs.

The three individual observations of NGC 1313 X-1 show evidence for line variability (see, for example, Ne x in Extended Data Fig. 5). Absorption is detected in the first two observations, while the emission lines are stronger in observation 3 where their flux is twice that seen in observation 1 (see Methods). Emission lines are weaker in observation 2 and show a decrease in the ionization parameter. We do not detect significant absorption in observation 3. In Fig. 2 we show the ratios of the RGS spectra between the individual exposures, which confirm the variability of both absorption and emission lines. We do not find a significant trend in the strength of the features with the spectral hardness of the source, most probably because the spectral states of the three observations are very similar11,12.

Spectral fits performed using only the RGS data (that is, excluding the PN data) from the three 100ks exposures confirmed the detection of the emission and absorption components (see Methods). In Fig. 3 we show the significance obtained adopting 500 km s$^{-1}$ and 10,000 km s$^{-1}$ line widths; negative values indicate absorption lines. Each emission line is detected individually at 3$\sigma$, confirming the $>5\sigma$ detection obtained with the CIE emission model which treats all of the lines consistently. Ne x and Ne x blueshifted absorption is also individually detected between 3$\sigma$ and 5$\sigma$, in agreement with the photoionization code.
The emission lines show comparable fluxes of $2.5 \times 10^{-6}$ photons s$^{-1}$ cm$^{-2}$ and equivalent widths of 15–30 mÅ, while the absorption lines have equivalent widths from 15 mÅ up to 250 mÅ. Lines associated with warm absorbers around active galactic nuclei typically have similar equivalent widths, but different dominant species: the O vii and Ne ix triplets and the common Fe xvii unresolved transition array (15–17 Å). Galactic X-ray binaries and microquasars also show comparable equivalent widths and similar ionic species, for example, Ne x and O viii, but intercombination transitions may play an important role.

**Figure 1** | Simultaneous spectral fits to the stacked XMM-Newton RGS and EPIC/PN spectra of NGC 1313 X-1. Main panel, the RGS stacked spectrum; inset, the PN stacked spectrum (same variables on axes). The rest-frame wavelengths of the most relevant transitions and some blueshifted lines are labelled (the dashed lines show the velocity shift). An isothermal emission model of gas in collisional ionization equilibrium describes most emission lines at rest. The absorption lines are reproduced with multi-phase models for gas in photoionization equilibrium. Red line, model consisting of rest-frame absorption and emission and a relativistically outflowing ($v = 0.2c$) photoionized absorber. Blue line, model that includes an additional broadened absorber ($v = 0.25c$). Error bars, $\pm 1\sigma$.

**Figure 2** | Ratios between the individual RGS spectra of NGC 1313 X-1. The RGS spectra were normalized by the spectral continuum and divided by that of observation 1 (obs 1). The absorption features (‘Abs’, 10.7–11.4 Å) change in observation 3 (obs 3). Rest-frame emission features also exhibit variability (see also Extended Data Fig. 5). Error bars, $\pm 1\sigma$. 

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The emission lines in NGC 1313 X-1 differ from those typically seen in active galactic nuclei and some X-ray binaries, but they are very similar to those produced by the accretion disk of the X-ray binary 4U 1626-6717, which may suggest an origin in a wind launched by a compact disk. The features seen in NGC 1313 X-1 are more difficult to detect than those seen in X-ray binaries because of the several orders of magnitude difference in distance (from a kiloparsec scale for the binaries in our Galaxy to the megaparsec scale for NGC 1313 X-1).

While the emission lines are seen at their rest-frame energies, the blueshifted absorption lines confirm the presence of an outflow, that is, photoionized gas within a wind8,12. The high ionization parameter and outflow velocity suggests an accretion-disk-wind origin similar to that of Galactic black hole binaries14, but with far larger velocities and therefore energetics (see Methods for possible interpretations). The fact that we detect both emission and absorption lines—the latter being line-of-sight dependent—requires that NGC 1313 X-1 is being seen at a moderate inclination angle (assuming an equatorial wind)12.

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Figure 3 | Significance of the features in the NGC 1313 X-1 RGS stacked spectrum. Shown is the line significance obtained by Gaussian fitting over the 7–27 Å wavelength range with increments of 0.05 Å and negative values indicating absorption lines. The solid and dashed lines indicate the line significance obtained with 500 km s\(^{-1}\) and 10,000 km s\(^{-1}\) widths, respectively. Ne x, Fe xvii, and O viii emission lines are individually detected at 3\(\sigma\), and combined provide an 8\(\sigma\) detection. Ne x blueshifted absorption is clearly detected up to 5\(\sigma\), showing widths larger than the emission lines.

Figure 4 | Best fit to the stacked XMM-Newton RGS spectrum of NGC 5408 X-1. Line labels are same as in Fig. 1. An isothermal emission model of gas in collisional ionization equilibrium describes most emission lines at rest. The absorption lines can be reproduced with gas in photoionization equilibrium. The red line is a model consisting of a single, relativistically outflowing (\(v = 0.22c\)), photoionized absorber. The blue line is a model that includes two absorbers (\(v_1 = 0.10c\) and \(v_2 = 0.22c\)). The absorption lines have widths of 500 ± 300 km s\(^{-1}\), while the emission lines are broader with \(\sigma_v = 2,000 ± 500\) km s\(^{-1}\). Error bars, ±1\(\sigma\).
with the difference between the widths and the Doppler shifts of the emission and absorption lines suggesting different spatial locations.

If collisional equilibrium applies, the most obvious explanation for the emission lines is either shock or collisional heating in the outflow with a range of velocities or between the outflow and the wind of the stellar companion as commonly seen in colliding-wind binaries. Such lines should also be present in other ULXs, but absorption features may be harder to detect if there is source confusion or if the spectral ‘state’ is hard.

NGC5408 X-1 also shows sharp emission features similar to those detected in NGC1313 X-1, including the Ne x and the O viii resonance lines and narrow absorption features at 12.2 Å, 15.5 Å and 17–18 Å (see Fig. 4, Extended Data Fig. 6, and Methods for details). The strongest emission lines are individually detected at 5σ, while the absorption features have lower significance (about 4σ in total). Most features can be described by an isothermal emission model of gas in collisional ionization equilibrium (temperature \( T \approx 3 \text{ keV} \)) and a relativistically outflowing (velocity \( v \approx 0.2c \)) photoionized gas model. The main absorbers in NGC5408 X-1 and NGC1313 X-1 have comparable outflow velocities (\( v \approx 0.2c \)), supporting the idea that they could have the same origin although the wind may be more structured in NGC5408 X-1 (see Methods).

NGC6946 X-1 exhibits the O viii (19.0 Å) and Ne ix (13.45 Å) emission lines and a feature at \( \sim 11.0 \text{ Å} \) that could be attributed to either higher-ionization Fe xii–xiii emission lines or to an absorption edge. Its very low continuum prevents the detection of any absorption lines. The emission lines that appear in the two ultraluminous X-ray sources NGC 1313 X-1 and NGC 5408 X-1 are probably associated with collisional shock heating between the circumsystem gas and the outflowing wind that we have now identified in the form of absorption lines. This result suggests that the accretion flow in some ULXs can be associated with powerful winds that leave their imprint in emission and absorption lines and are able to produce the common residuals in the high-quality CCD-resolution spectra of the most bright, well studied ULXs, for example, NGC 1313 X-1, Ho IX X-1, Ho II X-1, NGC 555 X-1, NGC 5204 X-1, NGC 5408 X-1 and NGC 6946 X-1.

Online Content Methods, along with any additional 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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1. Bachetti, M. et al. An ultraluminous X-ray source powered by an accreting neutron star. Nature 514, 202–204 (2014).
2. Shakura, N. I. & Sunyaev, R. A. Black holes in binary systems: observational appearance. Astron. Astrophys. 24, 337–355 (1973).
3. Poutaney, J. et al. Supercritically accreting stellar mass black holes as ultraluminous X-ray sources. Mon. Not. R. Astron. Soc. 377, 1187–1194 (2007).
4. King, A. R. et al. Ultraluminous X-ray sources in external galaxies. Astrophys. J. 552, L109–L112 (2001).
5. Pavlinsky, D. R., Strohmayer, T. E. & Mushotzky, R. F. A 400 solar mass black hole in the ultraluminous X-ray source M82 X-1 accreting close to its Eddington limit. Nature 513, 74–76 (2014).
6. Stobbart, A.-M., Roberts, T. F. & Wilms, J. XMM-Newton observations of the brightest ultraluminous X-ray sources. Mon. Not. R. Astron. Soc. 368, 397–413 (2006).
7. Bachetti, M. et al. The ultraluminous X-ray sources NGC 1313 X-1 and X-2: a broadband study with NuSTAR and XMM-Newton. Astrophys. J. 778, L163–L173 (2013).
8. Middleton, M. J., Walton, D. J., Roberts, T. P. & Heil, L. Broad absorption features in wind-dominated ultraluminous X-ray sources? Mon. Not. R. Astron. Soc. 438, L51–L55 (2014).
9. King, A. & Pounds, K. Powerful outflows and feedback from active galactic nuclei. Annu. Rev. Astron. Astrophys. 53, 115–154 (2015).
10. King, A. & Muldrew, S. I. Black hole winds II: hyper-Eddington winds and feedback. Mon. Not. R. Astron. Soc. 455, 1211–1217 (2016).
11. Gladstone, J. C., Roberts, T. P. & Done, C. The ultraluminous state. Mon. Not. R. Astron. Soc. 397, 1836–1851 (2009).
12. Middleton, M. J. et al. Diagnosing the accretion flow in ULXs using soft X-ray atomic features. Mon. Not. R. Astron. Soc. 454, 3134–3142 (2015).
13. Kaspi, S. et al. The ionized gas and nuclear environment in NGC 3783. I. Time-averaged 900 kiloarcsecond Chandra grating spectroscopy. Astrophys. J. 574, 643–662 (2002).
14. Ponti, G. et al. Ubiquitous equatorial accretion disc winds in black hole soft states. Mon. Not. R. Astron. Soc. 422, L11–L15 (2012).
15. Miller, J. M. et al. The accretion disk wind in the black hole GRO J1655–40. Astrophys. J. 680, 1359–1377 (2008).
16. Marshall, H. L., Canizares, C. R. & Schulz, N. S. The high-resolution X-ray spectrum of SS 433 using the Chandra HETGS. Astrophys. J. 564, 941–952 (2002).
17. Schulz, N. S. et al. Double-peaked X-ray lines from the oxygen/neon-rich accretion disk in 4U 1626–67. Astrophys. J. 563, 941–949 (2001).
18. Cooke, B. A., Fabian, A. C. & Pringle, J. E. Upper limits to X-ray emission from supercritical stellar winds. Nature 273, 645–646 (1978).
19. Oskinova, L. M. Evolution of X-ray emission from young massive star clusters. Mon. Not. R. Astron. Soc. 361, 679–694 (2005).

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Author Contributions C.P. wrote the manuscript with comments from all authors, and analysed the XMM-Newton data. Both M.J.M. and A.C.F. made substantial contributions to the overall science case and 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 C.P. (cpinto@ast.cam.ac.uk).

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METHODS

Data reduction. The XMM-Newton satellite is equipped with two types of X-ray detectors: the CCD-type European Photon Imaging Cameras (EPICs)\textsuperscript{20,21} and the Reflection Grating Spectrometers (RGSs)\textsuperscript{22}. The EPICs are MOS and PN. The RGS camera consists of two similar detectors, which have high effective area and high spectral resolution between 6 Å and 38 Å.

All the observations of the sources have been reduced with the XMM-Newton Science Analysis System (SAS)\textsuperscript{13.5.0} (http://www.cosmos.esa.int/web/xmm-newton). We correct for contamination from soft-proton flares following the XMM-SAS standard procedures. For each source and exposure, we extracted the first-order RGS spectra in a cross-dispersion region of 1 arcmin width, centred on the emission peak. We have extracted background spectra by selecting photons beyond the 98% of source point-spread function. The background spectra were comparable to those from blank field observations. We extracted the MOS and PN images in the RGS (0.35–1.8 keV) energy band and stacked them all with the ermosaic SAS task (see Extended Data Figs 1 and 3). We also extracted EPIC MOS and PN spectra from within a circular region of 1 arcmin diameter centred on the emission peak. The background spectra were extracted from within a 1 arcmin circle in a nearby region on the same chip, but away from bright sources and the readout direction. As the EPIC/PN spectra contain the majority of the counts and the residuals have been shown to not be instrumental in origin\textsuperscript{23}, we discard the EPIC/MOS spectra from our analysis. The total clean exposure times are quoted in Extended Data Table 1.

Sample size. No statistical methods were used to predetermine sample size.

EPIC + RGS spectral modelling. We fit the EPIC/PN and RGS spectra (with the SPEX package; http://www.iron.nl/spez) simultaneously to constrain both the broad-band continuum and describe the atomic features. Importantly, we fit across individual spectra in each observation rather than stacking the data in order to avoid any spurious features resulting from different pointing and background subtraction, which differ between RGS 1 and 2. We bin both the RGS and PN spectra in channels equal to 1/3 of the PSF, and use C-statistics, because it provides the optimal spectral binning and avoids over-sampling.

The phenomenological continuum model we apply to the data is a combination of soft blackbody with temperature $T \approx (2.5-3.0) \times 10^5$ K and power-law emission components with photon index $\Gamma \approx 1.9$ extending to high energies, both absorbed by neutral gas with a best-fit hydrogen column density $N_H = (1.8 \pm 0.1) \times 10^{22}$ cm$^{-2}$, which includes any intrinsic and Galactic absorption ($N_{\text{Gal}} = (4 \pm 10) \times 10^{21}$ cm$^{-2}$), adopting solar abundances\textsuperscript{23}.

The continuum of the three NGC 1313 X 1 observations shows little evidence for variability above 1 keV while the soft X-ray band is variable. All the model parameters for the RGS and EPIC spectra of the same observation are tied with each other while the continuum parameters (normalization and slope of the power law, normalization and temperature of the blackbody) are uncoupled between different observations. We detect a complex of emission and absorption lines (see Fig. 1). Under the first-order assumption that the lines are unchanging between observations, we also tie the parameters of the absorption and emission-line models for the different observations in order to increase the statistics.

The emission lines resolved by the RGS can be well modelled with a rest-frame, collisionally ionized gas (CIE model in SPEX), which is detected up to $8\sigma$ (see Fig. 1, red line, and Extended Data Table 2). The absorption-like features can be modelled with a two-phase absorbing gas in photoionization equilibrium. This can be described by a combination of two XABS models in SPEX. The $\Delta$CIE and the equivalent $\Delta \chi^2$ provided by each component, which indicates their improvement to the fit, are reported in Extended Data Table 2. The ionization parameters $\xi$ were tied between the different XABS models because a preliminary fit showed that, if they are left free to vary, they agree within error. One component is consistent with being at rest, while the other requires a high outflow velocity of $\sim 0.2 c$ (with $c \approx 3 \times 10^8$ m s$^{-1}$), while the other has a much stronger line which broadened to $75,000$ km s$^{-1}$ (at moderately relativistic velocities $\sim 0.25c$), and optically thick absorber (see blue circle in Fig. 1). The large velocity broadening ($\sim 0.1c$) in this latter model may explain why these features appear weak compared to the emission lines, however, an alternative reason may be variability between observations (indeed a trend in the strength of the residuals in the CCE spectra with spectral hardness was recently discovered\textsuperscript{24}). There is some degree of degeneracy in the absorption models. The inclusion of the broadened XABS 3 component strongly decreases the significance of the other two components XABS 1–2. Longer exposures are needed to better characterize the outflow.

In principle, the emission lines could also be produced by photoionized gas further away from the X-ray source. Indeed, the Fe xxvii 17 Å forbidden (f) line is much stronger than the 15 Å resonance (r) line which would suggest either photoionization or resonant absorption. As SPEX does not provide a model for line-emitting gas in photoionization equilibrium, we used the photomis model in XSPEC (http://heasarc.nasa.gov/docs/software/xspec/) to create a grid of photoionization emission models with $\log \xi$ from 1.0 to 4.0 with a 0.25 step size. The best fit still supports an Ne/Fe $\geq 1$ abundance ratio. It is difficult to distinguish between photoionization and collisional ionization models as the results are comparable; deeper observations are necessary. Alternatively, the emission features may originate from recombination of highly ionized gas within the wind or in a distant region, which is expected if photoionization occurs. However, a recombination model does not describe the lines satisfactorily. A shock between the outflow and the low density material in the surrounding nebula is also ruled out owing to the substantial X-ray brightness and the size of the X-ray source (see Extended Data Fig. 2) which is far more spatially compact (<116 pc) than the surrounding nebula (240–800 pc)\textsuperscript{28}.

RGS-only spectral modelling. We performed RGS-only spectral fits to check the line detection. We removed the EPIC-PN data and froze the continuum parameters to the values obtained with the simultaneous EPIC–RGS fit. We used Model 1 (with two narrow absorbers) and confirmed the need for both rest-frame emission and absorption lines. Despite the larger count rate, EPIC-PN does not change the detection significance overwhelmingly owing to its poorer spectral resolution with respect to RGS in the soft X-ray band.

The individual RGS spectra for each observation of NGC 1313 X 1 show changes in absorption line strengths (see Extended Data Fig. 5). In order to study the variability of the features, we have fitted the RGS spectra for the individual exposures with a simple model consisting of one CIE line-emitting component and one XABS absorber. Absorption is detected in the first two observations with consistent parameters ($N_H = (2.0 \pm 0.4) \times 10^{22}$ cm$^{-2}$, $\xi = 200 \pm 70$ erg cm s$^{-1}$ m$^{-2}$, $v = 50,000 \pm 500$ km s$^{-1}$ with significance $>3\sigma$ in total for each observation), while the emission lines are stronger in observation 3 where their flux is twice that than seen in observation 1, but the temperature is consistent at $kT = 1.10 \pm 0.15$ keV ($\sim 1.3 \times 10^5$ K). Emission lines are weaker in observation 2 and show a decrease in the ionization parameter where the Fe xxvi and O vii lines (from cooler gas) are stronger than the Ne x and O viii lines. We do not detect significant absorption in observation 3.

RGS line significance. We have also confirmed the detection of each emission/absorption line by fitting the RGS spectra adopting the EPIC–RGS continuum and including a Gaussian spanning the 7–27 Å wavelength range in increments of $0.02 \mu$m (with widths from 500 km s$^{-1}$ (from simulation) to 75,000 km s$^{-1}$ (0.25c)). In Fig. 3 we show the significance obtained adopting 500 km s$^{-1}$ and 10,000 km s$^{-1}$ line widths, confirming the lines detected with the CIE emission model. RGS line broadening does not have a major effect on the detection. The absorption lines have a lower significance because velocity shift is an additional parameter. The strongest feature at 11.5 Å (identified as Ne ix bluishifted absorption) has a chi-squared $P$-value of $6 \times 10^{-7}$ (that is, $5\sigma$), whether we consider it as a sum of 2 strong narrow lines or a single broad line. However, if we take into account all the trials due to the spectral resolution bins and widths, we obtain a probability of $\sim 3 \times 10^{-6}$, which is above $4\sigma$. If we also include parameter space of bluishifted lines that are found at exactly the same velocity, for example, O v in at 16.0 Å and O vii at 18.0 Å, then we obtain a total significance above $5\sigma$.

In order to further check the robustness of our results, we adopt different Ne, Fe, and O abundances for the neutral absorbing gas. The neutral gas of NGC 1313...
provides the bulk of the N$_H$ and may have non-solar abundances; this in principle could affect the detection of features in the soft X-ray spectra.$^{29}$ We therefore re-fitted the RGS and, afterwards, the EPIC-RGS spectra, simultaneously, with interstellar abundances ranging from 0.1 to 2.0× solar. No significant difference was found and the detection level of the lines is unchanged; this was expected for several reasons: the strongest features imprinted by neutral gas are expected between 22.7 Å and 23.5 Å (oxygen K edge and 1s-2p line)$^{29}$ and the lines in the ULX spectra avoid the edges. In addition, as we anticipated, the lines are narrow and their detection is not affected by the continuum-like hydrogen absorption.

We have stacked the first order RGS 1-2 spectra from the individual exposures of the same source for plotting purposes only (the stacked spectrum has a much higher S/N ratio and simplifies the recognition of the lines). We have used the following advanced method to combine fluxed spectra$^{11}$ (that is, spectra in flux units). We first created individual fluxed spectra using the SAS task rgsfluxer and then averaged them with the SPEX tool rgsfluxcombine for RGS 1 and RGS 2, separately. We then ran again the rgsfluxcombine (option 2) to combine the stacked RGS 1 and 2 fluxed spectra into a final RGS spectrum for each ULX. Finally, we used the SPEX task rgs_fmat to produce the response matrix for the stacked fluxed spectrum (see the SPEX manual; http://www.sron.nl/spex). The stacked RGS spectra of the three ULXs are shown in Figs 1–4, and in Extended Data Fig. 4.

**Constraints on the energetics of the wind, and the black hole mass.** Here we try to place some constraints on the location of the wind seen in NGC1313 X-1 as well as the black hole mass, using as a template the parameters estimated for the extreme absorber, XABS 3 (see Extended Data Table 2). The ionization parameter is defined as $\zeta=I_{\text{local}}/n_L R^2$, where $I_{\text{local}}$ is the 1–1,000 Ry ionizing luminosity of the source, and $n_L$ and $R$ are the thickness, size, and number density of the absorbing region. This leads to $\zeta=R I_{\text{local}}/n_L (\Delta R/R)$, where $n_L$ is the column density. Since $\Delta R < R$, then $\zeta=R I_{\text{local}}/n_L (\Delta R/R) < 10^{20}$ cm$^{-2}$, but R must also be larger than the Schwarzschild radius $R_S=2GM/c^2$. Assuming the escape velocity to be equal to the wind speed ($v_0$), or in other words that the wind comes from a region where its speed equals the escape velocity, we obtain $v_0/R_S < 25$, which provides an upper limit on the black hole mass of 40,000 solar masses (for a region with thickness comparable to its size). A black hole with a stellar mass, that is, up to 100 solar masses, would imply a very thin region ($\Delta R < R$, see Extended Data Fig. 7). Throughout this calculation we adopted unity covering fraction.

It is interesting to compare the wind power to the source luminosity$^{21}$:

$$P_\text{wind} = 0.5 M v_0^2 = 2\pi R^2 n_L m_p v_0^2 / \zeta,$$

where $m_p$ is the proton mass and $\zeta$ the solid angle. Since $\zeta=L/M v_0 R^2$, we get $P_\text{wind}=2\pi L M v_0^2 / \zeta$, which for component XABS 3, provides $P_\text{wind}/L \approx 100$. This would imply a highly super-Eddington accretion rate, but could be regarded as an upper limit because a smaller outflow rate and kinetic power are obtained if either the covering fraction is lower than unity or the duty cycle is shorter$^{12}$. On the other hand, the wind speed that we measure is a lower limit because it is only maximal for sightlines into the direction of outflow. With the present data characterized by only a few unevenly sampled observations, we cannot accurately measure these parameters.

**NGC5408 X-1 spectral modelling.** An X-ray image of the ultraluminous X-ray source NGC5408 is shown in Extended Data Fig. 3 along with another bright X-ray source (X-2, hereafter) which is covered by the RGS slit. In order to accurately estimate the RGS spectral continuum, we need to estimate the contribution from each source. We have therefore extracted the EPIC-PN spectra in two circular regions of one arcmin centred on the two sources. The background was chosen from a source-free circular region on the same chip and away from the read-out direction. The EPIC spectrum of NGC5408 X-1 was modelled with a soft blackbody ($kT=0.14$ keV$\approx 1.6 \times 10^8 K$) and a power law ($\Gamma=2.6$). The X-2 EPIC spectrum is very well modelled by a single power-law component with $\Gamma=1.99 \pm 0.01$ and neutral column density of $(3.6 \pm 0.2) \times 10^{20}$ cm$^{-2}$, consistent with the H I maps$^{24}$. No features or residuals are detected in the X-2 EPIC spectrum; this is most probably a background AGN.

We have built up a spectral model comprising the continuum from both X-1 and X-2 EPIC spectra and applied it to the RGS stacked spectrum of NGC5408 X-1. We searched for residual emission and absorption features as we did for NGC1313 X-1 (that is, using a Gaussian line stepping in wavelength). In Extended Data Fig. 6 we show the line significance obtained with 500 km s$^{-1}$ and 10,000 km s$^{-1}$ widths; the results do not strongly depend on the linewidth. The rest-frame wavelengths of some relevant transitions are labelled. Ne x and O viii emission lines are detected at each 4$\sigma$. Blueshifted absorption is also clearly detected with the strongest features detected at 3$\sigma$ each (taking into account the number of velocity bins), which provides a detection >4$\sigma$ in total for blueshifted absorption at a velocity shift of about 66,000 km s$^{-1}$.

We proceed to test physical models for the features, first with an isothermal emission model of gas in collisional ionization equilibrium ($kT=3.0 \pm 0.5$ keV, $\Delta \chi^2=129$, d.o.f.=3 relative to the continuum-only fits). This is able to reproduce the Ne xii and O viii lines and the residual Fe xvi emission, but the O viii emission is underestimated (see red line in Fig. 4). To model the absorption features, we applied a photoionized absorber to the continuum components (blackbody and power-law) of NGC5408 X-1, leaving the continuum components of X-2 unabsorbed. Most features can be reproduced with a relativistically outflowing ($v=(0.22 \pm 0.01)c$, $\Delta \chi^2=35$, d.o.f.=3) photoionized gas model. A better description of the spectrum is obtained adding a cooler CIE ($kT=0.10 \pm 0.05$ keV, $\Delta \chi^2=15$, d.o.f.=2) to fit the O vii lines and a slower ($v=(0.10 \pm 0.01)c$, $\Delta \chi^2=20$, d.o.f.=3) photoionized absorber (again only applied to the X-1 continuum components, see blue line in Fig. 4). The absorption lines have a width of 500 $\pm$ 300 km s$^{-1}$, while the emission lines are broader with $\sigma_i=2,000 \pm 500$ km s$^{-1}$, which are similar to the resolved RGS lines in NGC1313 X-1. Solar abundances were adopted for all emission and absorption components. The highly significant, $v=0.22c$, absorber in NGC5408 X-1 has an ionization parameter $\zeta=50 \pm 30$ erg cm$^{-2}$ s$^{-1}$ and column density $N_H=(3.0 \pm 0.4) \times 10^{20}$ cm$^{-2}$, which are lower than in NGC1313 X-1, while their outflow velocities ($v\approx 0.2c$) are comparable.

20. Strüder, L. et al. The European Photon Imaging Camera on XMM-Newton: the pn-CCD camera. Astron. Astrophys. 365, L18–L26 (2001).
21. Turner, M. J. L. et al. The European Photon Imaging Camera on XMM-Newton: the MOS cameras. Astron. Astrophys. 365, L27–L35 (2001).
22. den Herder, J. W. et al. The Reflection Grating Spectrometer on board XMM-Newton. Astron. Astrophys. 365, L7–L17 (2001).
23. Roberts, T. P. et al. Chandra monitoring observations of the ultraluminous X-ray source NGC5204 X-1. Mon. Not. R. Astron. Soc. 371, 1877–1890 (2006).
24. Kalberla, P. M. W. et al. The Leiden/Argentine/Bonn (LAB) Survey of Galactic HI. Final data release of the combined LDS and IAR surveys with improved stray-radiation corrections. Astron. Astrophys. 440, 775–782 (2005).
25. Lodders, K. S. & Palme, H. Solar system elemental abundances in 2009. Meteorit. Planet. Sci. Suppl. 72, S154 (2009).
26. Nomoto, K. et al. Nucleosynthesis yields of core-collapse supernovae and supernovae, and galactic chemical evolution. Nucl. Phys. 777, 424–458 (2006).
27. Swartz, D. A. et al. The ultraluminous X-ray source population from the Chandra archive of galaxies. Astrophys. J. Suppl. Ser. 154, 519–539 (2004).
28. Pakull, M. W. & Minion, L. Optical counterparts of ultraluminous X-ray sources. Preprint at http://arxiv.org/abs/astro-ph/0202488 (2002).
29. Good, M. R., Roberts, T. P., Reeves, J. N. & Uttley, P. A deep XMM-Newton observation of the ultraluminous X-ray source Holmberg II X-1: the case against a 1000-M$_{\odot}$ black hole. Mon. Not. R. Astron. Soc. 365, 191–198 (2006).
30. Pinto, C., Kaastra, J. S., Costantini, E. & de Vries, C. Interstellar medium composition through X-ray spectroscopy of low-mass X-ray binaries. Astron. Astrophys. 551, A25–A35 (2013).
31. Kaastra, J. S. et al. Multimwavelength campaign on Mrk 509. II. Analysis of high-quality Reflection Grating Spectrometer spectra. Astron. Astrophys. 534, A37–A52 (2011).
32. King, A. L. et al. Regulation of black hole winds and jets across the mass scale. Astron. Astrophys. J. 762, 108–120 (2013).
Extended Data Figure 1 | EPIC MOS+ PN stacked image of NGC 1313.

The circular source extraction regions (large white circles) have a diameter of 1 arcmin. The small region to the south of X-1 (small white circle) is a star-forming region near the galactic centre, orders of magnitude fainter across the 0.3–10 keV bandpass than X-1. The strip enclosed within dashed yellow lines is the RGS extraction region. Counts per pixel are colour coded (key at bottom).
Extended Data Figure 2 | ACIS image of NGC 1313 X-1 and the nearby star-forming region, SFR. The ultraluminous X-ray source is the brightest object. The small circles have 6 arcsec radii, that is, 0.1 arcmin; the larger circle has 0.5 arcmin radius. Counts per pixel are colour coded (key at bottom).
Extended Data Figure 3 | EPIC MOS+ PN stacked images of NGC 5408 and NGC 6946. a, NGC 5408; b, NGC 6946. The ultraluminous X-ray sources are the brightest objects in both images. Additional, nearby X-ray bright sources—mostly high-mass X-ray binaries and background active galactic nuclei—can be seen. The white circular source extraction regions have a diameter of 1 arcmin. Counts per pixel are colour coded (key at bottom).
Extended Data Figure 4 | XMM-Newton/RGS stacked spectra of the brightest ULXs (X-1) in NGC 1313, NGC 5408 and NGC 6946. Spectra are in flux units. The rest-frame wavelengths of relevant transitions are given as vertical red dashed lines, labelled with the transition. The spectra have been re-binned for display purposes. Error bars, ±1σ.
Extended Data Figure 5 | XMM-Newton RGS spectra and best-fitting model to each observation of NGC 1313 X-1. Spectra are in flux units. The rest-frame wavelengths of the most relevant emission lines (green vertical dashed lines) are shown, labelled with the transition in red, and the rest-frame wavelengths of the blueshifted absorption lines are shown by the position of the transition in blue. Obs 1 shows both absorption and emission lines. Obs 2 is dominated by absorption, while obs 3 shows mostly emission features. Error bars, ±1σ.
Extended Data Figure 6 | Significance of the features in the NGC 5408 X-1 RGS stacked spectrum. Negative values refer to absorption lines (see also Fig. 3 for NGC 1313 X-1). The solid and dashed curves show the line significance obtained with 500 km s\(^{-1}\) and 10,000 km s\(^{-1}\) widths, respectively. The dark and light grey regions enclose points within 2\(\sigma\) and 3\(\sigma\) confidence levels, respectively. Relevant transitions are labelled in red.
Extended Data Figure 7 | Constraints on the location of the extreme absorber, XABS 3, and mass of the compact object. The white area shows the acceptable values between the Schwarzschild radius ($R_S$, bottom oblique line), the relation $R = f(L_{ion}, N_H, \xi)$, which is given by $\xi = L/n_H R^2$ (dotted horizontal line), and the radius assuming the escape velocity to be equal to the wind speed ($v_w = 0.2c$, top oblique line, where $M$ and $M_{sun}$ are the compact object and solar masses, respectively). The red arrows show the maximum radius and the upper limit for a compact object with a $100M_{sun}$ mass.
### Extended Data Table 1 | Summary of the XMM-Newton observations

| Source      | Observation ID                                      | $t_{\text{TOT}}$ (ks) | $L_{0.3-10\text{keV}}$ (erg s$^{-1}$) |
|-------------|-----------------------------------------------------|------------------------|---------------------------------------|
| NGC 1313 X-1| 0405090101, 0693850501, 0693851201                  | 345.6                  | $1.04 \times 10^6$                   |
| NGC 5408 X-1| 0302900101, 0500750101, 0653380201, 0653380401, 0653380501 | 644.9                  | $2.01 \times 10^6$                   |
| NGC 6946 X-1| 0691570101                                          | 110.0                  | $0.97 \times 10^6$                   |

$t_{\text{TOT}}$: exposure times after data reduction; $L_{0.3-10\text{keV}}$: average de-absorbed luminosities.
Extended Data Table 2 | XMM-Newton EPIC-RGS spectral modelling

### Model 1 with narrow lines

| Parameter      | CIE    | XABS 1 | XABS 2 |
|----------------|--------|--------|--------|
| \(N_{\text{CIE}}\) or \(N_{\text{H,XABS}}\) | 3.1 ± 0.4 | 1.5 ± 0.3 × 10^2 | 5 ± 1 × 10^3 |
| \(T_{\text{CIE}}\) or \(\zeta_{\text{XABS}}\) | 0.85 ± 0.03 | 2.20 ± 0.04 | 2.20 coupled |
| \(v_x\) | 10 (< 500) | 10 coupled | 10 coupled |
| \(v_{\text{outflow}}\) | =0 | 0 (> -3 × 10^2) | -6.5 ± 0.2 × 10^4 |
| O/Fe | 1.0 ± 0.2 | 1.0 coupled | 1.0 coupled |
| Ne/Fe | 1.8 ± 0.4 | 1.8 coupled | 1.8 coupled |
| Mg/Fe | 2.1 ± 0.5 | 2.1 coupled | 2.1 coupled |
| \(\Delta \chi^2, \Delta \text{d.o.f.}\) | 87, 114, 6 | 130, 65, 3 | 48, 20, 3 |

### Model 2 with broad lines

| Parameter      | CIE    | XABS 1 | XABS 2 | XABS 3 |
|----------------|--------|--------|--------|--------|
| \(N_{\text{CIE}}\) or \(N_{\text{H,XABS}}\) | 3.0 ± 0.4 | 3.8 ± 1.3 × 10^3 | 3.1 ± 1.0 × 10^3 | 1.1 ± 0.2 |
| \(T_{\text{CIE}}\) or \(\zeta_{\text{XABS}}\) | 0.80 ± 0.03 | 2.29 ± 0.09 | 2.29 coupled | 4.55 ± 0.22 |
| \(v_x\) | 1250 ± 600 | 10 (< 20) | 10 (< 20) | 3.0 ± 1.5 × 10^4 |
| \(v_{\text{outflow}}\) | =0 | 0 (> -3 × 10^2) | -3.9 ± 0.2 × 10^4 | -7.5 ± 1.5 × 10^4 |
| O/Fe | 1.38 ± 0.16 | 1.38 coupled | 1.38 coupled | 1.38 coupled |
| Ne/Fe | 3.88 ± 0.91 | 3.87 coupled | 3.87 coupled | 3.87 coupled |
| Mg/Fe | 3.33 ± 0.50 | 3.33 coupled | 3.33 coupled | 3.33 coupled |
| \(\Delta \chi^2, \Delta \text{d.o.f.}\) | 86, 107, 6 | 30, 15, 4 | 12, 10, 4 | 150, 41, 4 |

The table is divided into two blocks to detail the results obtained with Model 1 (narrow absorption and emission lines) and Model 2 (Model 1 with an additional velocity-broadened absorption component). The CIE normalizations \(N_{\text{CIE}}\) (0.3–10 keV luminosity) and temperatures \(T_{\text{CIE}}\) (in keV, units) are in units of \(10^{38}\) erg s\(^{-1}\) and keV, respectively; the XABS column densities \(N_{\text{H,XABS}}\) and ionization parameters \(\xi_{\text{XABS}}\) are reported in units of \(10^{24}\) cm\(^{-2}\) and \(\log([\text{erg cm}^{-2} \text{s}^{-1}])\), respectively; both velocity broadening \(v_x\) and outflow velocity are in km s\(^{-1}\). The abundances are relative to iron, whose abundance is fixed to be solar\(^{25}\). Errors are ±1σ.