A white dwarf accreting planetary material determined from X-ray observations

The atmospheres of a large proportion of white dwarf stars are polluted by heavy elements\(^1\) that are expected to sink out of visible layers on short timescales\(^2,3\). This has been interpreted as a signature of ongoing accretion of debris from asteroids\(^4\), comets\(^5\) and giant planets\(^6\). This scenario is supported by the detection of debris discs\(^7\) and transits of planetary fragments\(^8\) around some white dwarfs. However, photospheric metals are only indirect evidence for ongoing accretion, and the inferred accretion rates and parent body compositions depend on models of diffusion and mixing processes within the white dwarf atmosphere\(^9\)\(^–\)\(^11\). Here we report a 4.4 \(\sigma\) detection of X-rays from a polluted white dwarf, G29–38. From the measured X-ray luminosity, we derive an instantaneous accretion rate of \(M_X = 1.63^{+2.09}_{-0.46} \times 10^9\) g s\(^{-1}\), which is independent of stellar atmosphere models. This rate is higher than estimates from past studies of the photospheric abundances of G29–38, suggesting that convective overshoot may be needed to model the spectra of debris-accreting white dwarfs. We measure a low plasma temperature of \(k_B T \approx 0.5 \pm 0.2\) keV, corroborating the predicted bombardment solution for white dwarfs accreting at low accretion rates\(^12,13\).

G29–38 is among the 100 closest white dwarfs and has hence been subject to detailed studies across most wavelength ranges. Whereas the detection of an infrared excess was initially interpreted as being most likely the signature of a brown dwarf, an origin linked to circumstellar dust was also discussed\(^14\). Subsequent ultraviolet spectroscopy revealed trace metals in the hydrogen atmosphere of the white dwarf\(^9\), which were interpreted as evidence for ongoing accretion from a compact dusty debris disk that formed from the tidal disruption of an asteroid\(^10\). Assuming that the white dwarf atmosphere is in an equilibrium between accretion and gravitational settling leads to a predicted accretion rate\(^17\) of \(6.5 \times 10^7\) g s\(^{-1}\). There are now more than a thousand known metal-polluted white dwarfs\(^18\), yet the evidence for ongoing accretion remains circumstantial, based on atmospheric abundances.

White dwarf accretion should be accompanied by intense heating of the infalling material, sufficient to promote cooling via X-ray emission\(^10\). This has been observed directly for white dwarfs accreting from stellar companions\(^11,12,13,20\), but never for a white dwarf accreting planetary debris. An \(\textit{XMM-Newton}\) observation of G29–38 resulted in a non-detection due to a nearby bright X-ray source, placing an upper limit\(^20\) on the accretion rate of \(2 \times 10^9\) g s\(^{-1}\). A handful of metal-polluted white dwarfs have been the subject of X-ray studies, resulting so far only in upper limits, rather than firm detections\(^21\).

G29–38 was observed with \(\textit{Chandra}\)\(^22\) ACIS-S in September 2020, with a total exposure time of 106.33 ks (see Extended Data Table 1 for details). The sky location of the X-ray photons is shown in Fig. 1. The data reduction used three standard \(\textit{Chandra}\) science bands: soft (0.5–1.2 keV), soft + medium (0.5–2.0 keV) and broad (0.5–7.0 keV). Within 1 arcsec of our target, we detected five X-ray events, with one medium and four soft band events. Using a Bayesian approach, we found the 68% confidence interval on the broad band source count rate to be (2.4–6.6) \(\times 10^5\) counts per second (see Extended Data Table 4 for other bands).

Fig. 2 shows the sky location of the soft + medium band events, which are fully consistent with the uncertainty on the position from the \(\textit{Chandra}\) ACIS-S astrometry. We computed the probability of the observed events arising by chance. A standard aperture photometry approach (Methods) revealed source counts of 4.5 and 5, in the soft, soft + medium and broad bands, respectively, with measured backgrounds of 0.10, 0.21 and 0.57 counts per 1 arcsec aperture. Using the Poisson distribution, we found the statistical significance of the source counts in the three bands to be 4.62, 4.71 and 3.64 \(\sigma\) (Extended Data Table 2). Accounting for the astrometric uncertainty by centring the aperture on the detected source position (Fig. 2), and using a smaller radius of 0.5 arcsec, which is appropriate for soft sources in ACIS-S, increases the detection significance to 5.65, 5.94 and 5.06 \(\sigma\) in the three science bands, respectively.

As confirmation that the observed source counts originated from the target, and not a background source, we used a source detection algorithm (Methods) to derive a sky density of sources at the depth of the ACIS-S observations. In the soft, soft + medium, and broad bands, this analysis resulted in 6, 24 and 32 sources, respectively (excluding

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our target), setting the background source sky density over the whole image to $\rho_\text{bg} = 2 \times 10^{-3}, 9 \times 10^{-3}$ and $13 \times 10^{-3}$ arcsec$^{-2}$ (Extended Data Table 3). The detected sources comprise real astrophysical sources and spurious detections arising from background counts. Interpreting this as the probability of a chance alignment, we were able to confirm that the source events originated from G29–38 at 4.1, 3.8 and 3.7σ. Finally, we performed a Monte Carlo aperture photometry analysis (Methods and Extended Data Fig. 2) in which, in the soft band image, only 0.001% of test apertures retrieved four events, with none retrieving more than four, thus enabling chance alignment with a background source to be ruled out at 4.4σ. We conclude that the four recorded events in the standard soft science band reveal a more than 4σ detection of X-rays from G29–38.

The energies of the five recorded events within 1 arcsec of our target are all in the range of 0.7–1.4 keV, with four below 1 keV. The detection of most photons below 1 keV strongly suggests that the X-ray emission spectrum is very soft, and thus emitted from a relatively low-temperature plasma. To determine the best-fitting plasma temperature, $T_X$, we initially adopted an optically thin isothermal plasma model and tested three distinct sets of abundances: Solar, bulk Earth and the spectroscopically determined photospheric abundances of G29–38 (ref. 19). The plasma temperatures were consistent, with the photospheric abundances corresponding to $k_B T_X = 0.49^{+0.27}_{-0.25}$ keV (Extended Data Table S5), where $k_B$ is the Boltzmann constant.

Even though no debris-accreting white dwarf has previously been detected at X-ray wavelengths, X-ray detections of white dwarfs in binaries are common, as they have higher accretion rates. Our measured plasma temperature of 0.5 keV is much lower than that found for white dwarfs accreting from stellar companions, which typically accrete at $\gtrsim 10^{16}$ g s$^{-1}$ and have plasma temperatures$^9$ in the range of 5–50 keV. This result is robust because the sensitivity of the ACIS-S detector peaks between 1 and 6.5 keV (Extended Data Fig. 3) and emission with the same luminosity at higher temperatures would have been readily detected. Measuring such a low plasma temperature points to a heating mechanism that is distinct from the strong stand-off shocks thought to heat the infalling material at higher accretion rates$^{20}$, in which a shock is formed above the stellar surface. Instead, at the low accretion rate we observe for G29–38, the accreting material may have insufficient density to establish a shock above the stellar surface, and the material may impact directly onto the white dwarf surface: the proposed ‘bombardment’ solution$^{12,13}$. For a white dwarf with the parameters of G29–38 (mass $M_{WD} = 0.6 M_\odot$ and radius $R_{WD} = 0.0129 R_\odot$), the plasma temperature arising from accretion in the bombardment scenario has been predicted by Kuijpers and Pringle$^{12}$ (see their equation (9)) to be $k_B T_X = 0.6$ keV, consistent with our measured plasma temperature.

To determine the X-ray flux, we adopted a more physically motivated spectral model that combines emission from an optically thin plasma at a range of temperatures (a cooling-flow model; see Methods). Integrating the best-fit model over the ACIS-S passband we derive an X-ray flux of $F_X (0.3–7.0 \text{ keV}) = 1.97^{+1.55}_{-1.48} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$. The distance to G29–38 ($d = 17.53 \pm 0.01$ pc; ref. 24) implies an X-ray luminosity of $L_X (0.3–7.0 \text{ keV}) = 7.24^{+2.56}_{-1.75} \times 10^{25}$ erg s$^{-1}$. This is many orders of magnitude lower than observed for white dwarfs accreting from main-sequence companions (typically $L_X \approx 10^{29–33}$ erg s$^{-1}$).
Cyclotron emission cooling might radiate some of the accretion-induced luminosity at radio wavelengths if the magnetic field is strong enough\(^{26,27}\). At the 3\(\sigma\) upper limit on the magnetic field of G29–38 (1.5 kG; ref. 22) we find the maximum accretion rate increase due to cyclotron emission to be a factor of \(1.1^{+0.9}_{-0.6}\) (Extended Data Fig. 4), and for magnetic fields less than approximately 1 kG the predicted cyclotron cooling emission is negligible.

Accretion rates at metal-polluted white dwarfs are typically inferred indirectly from spectroscopic abundance measurements, using white dwarf atmospheric models to quantify the flux of metals moving through the photosphere\(^1\). The time-averaged accretion rate of G29–38 was previously inferred\(^{23,24}\) to be \(M = (5.0 \pm 1.3) \times 10^{-6} \) and \((6.5 \pm 1.6) \times 10^{-6} \) g s\(^{-1}\). Fig. 3 shows the X-ray accretion rates, and those derived from previous spectroscopic studies. Our observations establish an X-ray accretion rate that agrees to within a factor of 3 of those derived via the spectroscopic method. Recent results from three-dimensional (3D) radiation–hydrodynamic simulations predict an increase in accretion rate inferred from spectroscopic observations due to convective overshoot\(^2\). At the effective temperature of G29–38 (approximately 11,500–12,000 K), the increase is predicted to be a factor of 3–4. Thus, the 3D accretion rate is predicted to be approximately \(2 \times 10^9 \) g s\(^{-1}\), which is a closer match to the best fitting X-ray accretion rate (Fig. 3). The diffusion timescale is also predicted to increase from days to years, which is more consistent with the lack of time variability of metal lines in G29–38 (ref. \(^{22}\)).

**Online content**

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**Fig. 3** Accretion rates inferred from the measured X-ray flux. Accretion rates from the isothermal and cooling flow models. We show results for two plasma abundances: bulk Earth and photospheric\(^2\). The filled horizontal bands represent the 68% confidence interval on the four accretion rates, and for readability the four open data points are offset in effective temperature around 11,820 K. The X-ray accretion rates are computed using equation (1). Using equation (S), the accretion rates inferred from spectroscopic observations are represented by solid lines for a 0.6M\(_\odot\) white dwarf, assuming bulk Earth composition, such that the observed calcium abundance\(^17\) of log(\(\text{Ca/H}\)) = -6.58 ± 0.12 makes up 1.6% of the accreted material. Accretion rates from models that include\(^{26,27}\) or omit\(^1\) convective overshoot mixing are shown in green or magenta, respectively, with 1\(\sigma\) uncertainties (dashed lines) propagated from the spectroscopic abundance measurement. Also shown in solid circles are the previously published inferred accretion rates for G29–38 in blue\(^{26}\) and orange\(^{27}\).

We estimate the instantaneous accretion rate using\(^{30}\)

\[
M_k = \frac{2}{A^2} \frac{R_{WD}}{GM_{WD}},
\]

where \(G\) is the gravitational constant, the factor 2 accounts for 50% of the emitted photons being directed back towards the star\(^{23}\) and the constant \(A\) quantifies the fraction of the total accretion-induced luminosity carried in the observed band. To calculate the X-ray accretion rate from our observations, we take the limiting case that the total luminosity is equivalent to the observed X-ray luminosity (\(A = 1\)). Fig. 3 shows the 68% confidence interval on the instantaneous accretion rate derived for the two plasma models (isothermal and cooling flow) and two debris abundances (bulk Earth and photospheric) across the range of uncertainty on the photospheric effective temperature of G29–38. Using equation (1), the bulk Earth abundances and cooling flow model, we find the best-fit instantaneous accretion rate to be \(M_k = (0.3 – 7.0 \text{ keV}) = 1.63^{+1.29}_{-0.40} \times 10^{-9} \) g s\(^{-1}\). This is currently the only direct measurement of the instantaneous accretion rate of any white dwarf accreting planetary debris, providing the only way to validate the indirect accretion rates derived for a large number of white dwarfs from photospheric abundance analyses.

The observations provide robust constraints on hard X-ray emission (more than 2.0 keV) as the Chandra ACIS-S detector is most sensitive in the range of 1.0–6.5 keV (Extended Data Fig. 3), whereas appreciable emission is probably softward of the ACIS-S bandpass (less than 0.3–0.5 keV). To estimate the flux carried at unobserved wavelengths, we integrated the best-fit cooling flow model across the wider energy band 0.0136–100 keV (Methods). We found the flux in the wider integration band to be \(F_{X} = 0.0136 – 100 \text{ keV} = 4.34^{+1.98}_{-1.22} \times 10^{-16} \) erg s\(^{-1}\) cm\(^{-2}\). This represents a flux increase of a factor of \(2.2^{+2.6}_{-0.9}\) compared with the Chandra ACIS-S bandpass integration.
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Methods

Observations and data reduction
Our observations consisted of five exposures using Chandra ACIS-S carried out between 22 and 27 September 2020. Each observation had an exposure time between approximately 15 and 25 ks (Extended Data Table 1), with a total, merged exposure time of 106.33 ks, or 29.5 h. All observations were carried out with the ACIS-S instrument using the Gaia DR2 (ref. 34) proper motion-corrected coordinates of our target positioned on the S3 chip. The predicted X-ray luminosity was sufficiently low that our setup included the very faint mode that stores event grades in regions of 5 × 5 pixels, rather than the standard 3 × 3 pixels. This enables an improved identification and rejection of background events, particularly at hard and very soft energies.

The data reduction was performed using the software package Chandra Interactive Analysis of Observations (CIAO39). The reduction began by reprocessing the five observations using the chandra_repro package with standard grade, status and good time filters and faint background cleaning applied. We used merge_obs to merge the five observations into a single set of event files along with images, point spread function (PSF) maps and exposure maps. We performed this routine using combinations of the standard Chandra science energy bands: soft (0.5–1.2 keV), soft + medium (0.5–2.0 keV) and broad (0.5–7.0 keV).

During each merging routine, the PSF maps and exposure maps were generated for each band with exposure evaluated on 0.9 keV, which represents an approximate mean of the suspected source photon energies.

Statistical significance of detection
We initially investigate whether the detected events within 1 arcsec of our target amount to a statistically significant source. To determine the statistical significance of the detection, we used the Poisson distribution, which is appropriate for counting statistics with small numbers of events32. This enabled us to quantify the confidence with which we can rule out the null hypothesis that we detected no source photons. We defined a source region of 1 arcsec around the coordinates of our target—right ascension (RA) and declination (DEC) of (352.196185 ± 0.00004) and (+05.24686 ± 0.00003), respectively—which have been corrected to the J2020.73 epoch using the Gaia EDR3 (ref. 33) astrometry. The nearby background region was defined as a circle with a 52 arcsec radius, avoiding obvious point sources—such as the nearby bright source that contaminated previous XMM-Newton observations33 (for example, see Extended Data Fig. 1a–c)—and drops in sensitivity in the exposure map.

Extended Data Table 2 shows the source and background counts from the full, merged observation of 106.33 ks. The Poisson distribution gives the probability of receiving $N_B$ more counts, given an expected mean background, $b$, as

$$P(N_B) = \frac{b^{N_B} e^{-b}}{N_B!}. \tag{2}$$

We can therefore reject the null hypothesis that there are no source photons with a confidence level (CL) of $C_L = 100 \times (1 - P(N_B))$. In the soft, soft + medium and broad bands, we find CL = 99.99962%, 99.99975% and 99.97255%, respectively. The statistical significance, $s$, can be computed as

$$s = \text{erf}^{-1}(1 - P(N_B)) \sqrt{2}, \tag{3}$$

which for each of the three bands is $s = 4.62\sigma, 4.71\sigma$ and $3.64\sigma$, respectively. We note that adopting a smaller aperture with a radius of 0.5 arcsec, which is appropriate for soft sources with ACIS-S (see Figure 6.10 of the Chandra Proposers’ Observatory Guide version 23.0 (ref. 30) in which the enclosed fractional power is more than 50% for 0.5 arcsec apertures), and accounting for the astrometric uncertainty by centring the aperture on the locus of photons at the source position (Fig. 2) increases the detection significance in the three science bands to 5.65$\sigma$, 5.94$\sigma$ and 5.06$\sigma$, respectively. We conclude that, in all the three science bands considered, an X-ray source is detected at the expected position of our target, G29–38.

Count rates and confidence intervals
For each science band considered, we converted the number of counts to a count rate using the total exposure time of 106.33 ks. In the soft, soft + medium and broad bands we find count rates of $0.038^{+0.007}_{-0.002}$, $0.047^{+0.020}_{-0.023}$ and $0.047^{+0.024}_{-0.028}$ ks$^{-1}$ per 1 arcsec aperture, respectively. The 68% confidence interval on count rate across all three bands is $(2.1 \pm 7.0) \times 10^{-6}$ counts per second, whereas the 90% confidence interval spans $(1.3 \pm 9.0) \times 10^{-6}$ counts per second. The confidence intervals were calculated using a Bayesian approach to Poisson statistics, following the methodology in ref. 34. This uses a simple prior that requires a non-negative number of source counts.

Investigating positional uncertainty
The five recorded soft + medium band events within 1 arcsec of our target coordinates have a sky position that is shifted by approximately −0.5 arcsec in right ascension. In Fig. 2 we plot the sky position of the recorded events in the soft + medium band within 1 arcsec of our target. We find that all five of the photons in the soft + medium bands have sky locations consistent with the 1σ uncertainty on the target’s position, which arises from the astrometric uncertainty of the telescope itself. From Figure 5.4 of the Chandra Proposers’ Observatory Guide (version 23.0)30, the 68% confidence limit on the radial offset of a given target is 0.52 arcsec. This value was computed for observations between 2015 and 2020 by comparing the radial offset of Chandra sources with optical sources predominantly from the Tycho-2 catalogue. The solid, red circle in Fig. 2 shows the 68% confidence interval on the position of our target and illustrates the expected precision of the target position in our data. We find that all five events considered in our earlier statistics fall within this area.

Constraining source positional offset
The centre of the five photons attributed to our source exhibit an apparent offset compared to the Gaia EDR3 position of approximately −0.5 arcsec in RA. The mean coordinates, in (RA, DEC), of the five photons from the merged observations are (352.19606 ± 0.00004, 5.24684 ± 0.00005). Compared to the Gaia EDR3 expected position of our target, this represents an offset of $(-0.51 \pm 0.13, -0.07 \pm 0.17)$ arcsec. To investigate the cause for this offset we searched for optical counterparts in the full ACIS-S charge-coupled device (CCD) image, finding one additional X-ray source with a counterpart in Gaia EDR3. To identify counterparts in Gaia EDR3, a positional cross-match was performed, searching for sources within 5 arcsec of the sources detected with the source detection algorithm wavdetect30 (see next section and Extended Data Fig. 1) in the merged image for all three science bands (Extended Data Table 3). Excluding our target, the cross-match resulted in one Gaia EDR3 source with source ID 2661110815469507072. Corrected for proper motion, the expected coordinates of this source at the epoch of observation (J2020.73) are (352.18248 ± 0.00007, 5.341502 ± 0.000008). The output of wavdetect gives the coordinates for the centre of the detected source (352.18235 ± 0.00002, 5.341529 ± 0.000020). This leads to a positional offset between the Gaia EDR3 proper-motion-corrected position and the centre of the detected source in wavdetect of $(-0.46 \pm 0.08, +0.10 \pm 0.07)$ arcsec, which is consistent with the offset observed for our target. This offset can be observed in Extended Data Fig. If in which the Gaia position is shown in white and the wavdetect source is shown in cyan. The offset observed for our target and the only other Gaia source in the field are fully consistent to within 1σ, as can be observed in Fig. 2.
Ruling out background contamination

To determine the probability of chance alignment with a background source we follow two methodologies. In the first, we run a source-detection algorithm to provide an independent constraint on the number of sources at this depth of pointing. We rely on wavdetect\textsuperscript{35}, a wavelet-based algorithm included in the CIAO package, designed for the spatial analysis of Poisson count data. As recommended in the documentation, we set the sigthresh parameter, which defines the threshold for identifying a pixel as belonging to a source, to \( \text{SNR} = 10^{-6} \), which implies that approximately one identified source will be a false detection. We perform this analysis in all three of the standard bands considered in this study, and for two values of sigthresh, \( \sigma_1 \) and \( \sigma_2 \). In the first, we use \( \sigma_1 = 10^{-6} \), which is the recommended value for the number of pixels \((1.024 \times 1.024)\) of the S3 CCD. The second, more stringent, value of sigthresh, \( \sigma_2 = 5 \times 10^{-7} \), accounts for the ‘dead’ corners of the image that arise from aligning the CCD image with the world coordinate system. This results in an image with \( 1.414 \times 1.401 \) pixels. The results are given in Extended Data Table 3, and Extended Data Fig. 1 shows the sky location of the detected sources in all three science bands. Across the entire CCD image, we detect 7, 25 and 32 sources, in the soft, soft + medium and broad bands, respectively. We find that our target is not detected in the broad band image, regardless of the sigthresh value. In the soft band, the target is detected at the higher sigthresh value, but not with the more stringent value. In addition, in the soft + medium band we find that the source is detected in both cases. Dividing the total number of sources in each band by the field of view \((1.024 \times 0.4920 \text{arcsec}^2)\) reveals sky densities of \(2.76 \times 10^{-5}, 9.85 \times 10^{-5}\) and \(1.26 \times 10^{-4} \text{arcsec}^{-2}\), in the soft, soft + medium and broad bands, respectively. To estimate the probability of chance alignment with a background source, we multiply the sky density by an effective location error area. For this area we adopt the 90% confidence limit on the radial offset of ACIS-S targets, which is given as 0.72 arcsec (see Figure 5.4 of the Chandra Proposers’ Observatory Guide version 23.0 (ref. 1)).

We can therefore rule out chance alignment at a significance of \( \sigma = 4 \times 10^{-4}, 3.8 \times 10^{-4}\) or an confidence of 99.996%, 99.985% and 99.979%, respectively.

To further test this result, we performed a Monte Carlo aperture photometry experiment. We placed 100,000 apertures with 1 arcsec radii within 100 arcsec of the target. This area was chosen to confine the study to the region of the ACIS-S3 CCD where the PSF does not exhibit a significant gradient, as beyond approximately 120 arcsec the PSF increases significantly. This effect can be observed in the output of the wavdetect algorithm in the top panels of Extended Data Fig. 1, in which the sources detected near the edge of the CCD seem to be much larger. For the Monte Carlo aperture photometry test we make use of the Python package scpy\textsuperscript{17}, and in particular the KDTree module. This facilitates the rapid comparison of a large number of test aperture positions with those of recorded events from our observation. To estimate the true sky density of background sources we exclude the target and known nearby bright source using circular masks of radius 1 arcsec and 2.5 arcsec, respectively. The final number of test apertures was slightly reduced after the removal of the approximately 150 – 200 that fell within masked regions.

The results of this test on the soft and soft + medium band events are shown in Extended Data Fig. 2. In the soft band analysis, we find 1 in 99,828 test apertures \((0.001\%)\) retrieved 5 counts, whereas no test apertures found more than 4 counts. This enables us to rule out chance alignment with a background source at a significance of \(4 \times 10^{-4}\). In the soft + medium band, we find 56 in 99,852 test apertures \((0.056\%)\) have 5 or more counts, whereas 48 \((0.048\%)\) returned between 6 and 27 counts, enabling us to rule out chance alignment at the \(3.4\sigma\) level. The reason the chance-alignment significance is lower in the soft + medium band is not because there is any doubt about the source detection, but because (1) our source has a soft spectrum and so contributes little flux in the medium band, and (2) there is a much larger number of background sources in the medium band, as most X-ray sources are harder than our target, and because the effective area of the telescope is higher. This test also provides an empirical confirmation of the quoted expected backgrounds in Extended Data Table 2, with fewer than 10% and 20% of 1 arcsec test apertures returning any counts in the soft and soft + medium bands, respectively.

We have shown that the counts detected within 1 arcsec of our target coordinates enable the rejection of the null hypothesis—that no source counts were measured—with a conservative confidence of 99.975% – 99.9962\% (3.64 – 4.71\%). Using the recommended aperture size of 0.5 arcsec, and centring the aperture on the observed source position, we find the source significance increases to 5.06 – 5.91\%.

We have also shown that the observed position of the five recorded events is consistent with the expected position of our target, to within the 1\sigma astrometric uncertainty, which is further confirmed by comparison with the only other observed X-ray source with a Gaia EDR3 counterpart. We have tested the hypothesis that recorded source counts could have originated instead from a background source and, by constraining the sky density of sources at this depth of pointing using wavdetect, we rule out a chance alignment with a background source at a confidence of \(99.996\%\) and \(99.985\%\) \((4.1\) and \(3.8\)\) in the soft and soft + medium bands, respectively. Confirming these results with Monte Carlo aperture photometry, in the soft band, with 0.001% of test apertures returning four counts, chance alignment can be ruled out with a confidence of \(99.999\%\) \((4.4\)\). Given the high degree of confidence to which the observed events can be attributed to our target, G29 – 38, in the following we perform spectral modelling to derive the X-ray flux, luminosity and accretion rate.

Spectral model and debris composition

We perform a spectral analysis assuming two different optically thin plasma models and three distinct abundance profiles. The first model is a one-component, isothermal plasma implemented in the vwpacc model within the XSPEC software package (version 12.11.1)\textsuperscript{37}, which uses the AtomDB atomic database\textsuperscript{38}. The second model, mkcflow, is a cooling flow model that allows for a range of temperatures, with the relative emission measure for each temperature weighted by the inverse of its emissivity. We selected the option to use the AtomDB database. This cooling flow model is more physically motivated than the isothermal model and is likely to provide a better estimate of the X-ray flux beyond the observed bandpass. We fitted the mkcflow model by fixing the lowest temperature plasma at the lower limit of the model of \(k_B T = 0.08 \text{keV}\), only allowing the upper temperature of the range to vary, enabling a one-parameter fit. This models the emission from material heated to the upper temperature and then cooling to temperatures lower than can be detected with Chandra ACIS-S. The three abundance profiles we use are Solar\textsuperscript{39}, bulk Earth\textsuperscript{40} and the observed photospheric metal abundances\textsuperscript{41} of G29 – 38 with an equal number abundance of hydrogen. The composition of the infalling material is best described as a rocky, water-depleted, chondritic object\textsuperscript{42}, with detected lithophile (O, Si, Mg, Ca, Ti and Cr), siderophile (Fe) and atmophile (C) elements. If the heated plasma is formed sufficiently close to the stellar surface, such as in the bombardment scenario, the rocky accreted material may be mixed with photospheric hydrogen. However, we found that our results were not sensitive to the hydrogen abundance, because at the best-fit plasma temperatures (approximately 0.5 keV) the cooling is dominated by metal line emission. At the distance to G29 – 38, the interstellar column density is expected\textsuperscript{43} to be only around \(N_{\text{HI}} = 5.4 \times 10^{18} \text{cm}^{-2}\), which has a negligible effect in the Chandra ACIS-S passband (less than 0.5% absorption at 0.5 keV). The five events in the ACIS-S spectrum were fitted unbinned, using the C-statistic\textsuperscript{44}, and with no background subtraction.

Extended Data Figure 3a shows the spectral fits and Extended Data Table 5 shows the best-fit plasma temperatures for all six models, and
the 68% and 90% confidence intervals. The bulk Earth and photospheric models agree to within the 68% confidence interval. The observed photospheric abundances of G29–38 could be scaled by the microscopic diffusion timescale in the atmosphere to infer a more accurate accreted debris composition. The difference, however, would be small, and the agreement between the bulk Earth and photospheric models strongly suggests that the observations would not be sensitive to such a correction.

**Deriving X-ray flux**

We derive a total flux due to accretion by integrating the best-fit spectral models over a finite frequency (or energy) range. We find a robust lower limit on the X-ray flux of \( F_X (0.3 - 7.0 \text{ keV}) = 1.97 \pm 0.00 \times 10^{24} \text{ erg s}^{-1} \text{ cm}^{-2} \) by performing the integration only over the energies within the Chandra ACIS-S passband (0.3 - 7.0 keV). We also perform the integration across a slightly narrower band (0.5 - 7.0 keV) as the instrument sensitivity below 0.5 keV has degraded since launch and is now relatively low. These results, with their associated confidence intervals, are shown in Extended Data Table 6. With the lower limit on X-ray flux tightly constrained, providing an upper limit on the X-ray flux is more challenging. This is primarily due to the lack of observations between the very soft X-rays (approximately 0.1 keV) and the ultraviolet. There are no instruments currently equipped to perform observations at these extreme ultraviolet (EUV) wavelengths, so directly measuring the flux in this regime is, for now, impossible. The constant \( A \) included in equation (1) describes the predicted fraction of the total luminosity carried in the Chandra ACIS-S passband. Previous studies\(^{20,21}\) have made the approximation that \( A = 0.5 \) or 0.25. We provide an upper estimate of the X-ray and EUV flux by integrating the best-fit spectral models over a much wider energy range (0.0136 - 100 keV).

Model spectra over this broadband are plotted in Extended Data Fig. 3b and we include fluxes calculated for this broad band in Extended Data Table 6.

**Extended Data**

Extended Data Fig. 3c shows the X-ray flux computed in the three integration bands used in this analysis. For clarity, from here onwards we show results only from the cooling flow model (mkcflow) using the photospheric abundances. The use of the cooling flow model is designed to provide a realistic temperature distribution and hence realistic fluxes in the EUV band (it can be compared with the isothermal model in Extended Data Fig. 3b). From left to right in Extended Data Fig. 3c the size of the integration domain increases and, as expected, the best-fit X-ray flux (and therefore accretion rate) also increases, with the widest band (0.0136 - 100 keV) providing an upper estimate of the X-ray and EUV flux. The wider integration bands result in a best-fit accretion rate that is 2.2\(^{+1.55}_{-0.9}\) times higher than that derived from the ACIS-S passband, where the errors represent the 68% confidence interval. We note that the 68% and 90% upper bounds on the fluxes increase by a factor of approximately 10 and 100, respectively, due to the uncertain importance of the EUV band.

**X-ray luminosity**

We derive an X-ray luminosity from the X-ray flux measured in the previous section using \( L_X = 4 \pi d^2 F_X \) with the distance to G29–38 of \( d = (17.53 \pm 0.01) \) pc calculated from the Gaia EDR3 parallax. Extended Data Table 6 shows the best-fit X-ray luminosity for each of the energy ranges. From the robust lower limit on the X-ray flux, the best-fit X-ray luminosity from our observations is found to be \( L_X (0.3 - 7.0 \text{ keV}) = 7.24 \pm 1.76 \times 10^{25} \text{ erg s}^{-1} \), where the errors are indicative of the 68% confidence interval.

**X-ray accretion rates**

Here we estimate the instantaneous accretion rate using a simple model that has been used in studies of accreting white dwarfs\(^{20,21}\). In this model, infalling material reaches near-free-fall velocity, forming a heated plasma as the material approaches the white dwarf surface.\(^{20}\) The plasma must radiate outwards a total energy equivalent to the initial gravitational potential energy of the accreted material such that\(^{20}\)

\[
L_{tot} = \frac{1}{2} \frac{GM_W M}{R_{WD}}.
\]

where \( R_{WD} \) is the white dwarf radius at which infalling material impacts the atmosphere and the factor 1/2 accounts for 50% of emitted photons being directed back towards, and being absorbed by, the star\(^{20,25}\). We allow the emitting plasma to be formed by individual atoms reaching the white dwarf atmosphere in a scenario termed the ‘bombardment’ solution, which is relevant for low accretion rate systems\(^{12,13}\), such that the X-ray emitting plasma is formed at the white dwarf radius \( R_{WD} = 0.0129 \mu \text{ m} \). This scenario was hypothesized for white dwarfs accreting from main-sequence companions at low accretion rates, and predicts a plasma temperature (approximately 0.6 keV) comparable to that to which we have measured from our observations (0.5 keV). From the total luminosity, the X-ray luminosity can be written as \( L_X = A L_{tot} \), where the constant \( A \) accounts for the fraction of the flux emitted outside the observed passband. If the plasma cooling is entirely mediated by line cooling in the observed X-ray passband (0.3 - 7.0 keV), then \( A = 1 \). If the plasma experiences additional line cooling at harder or softer energies than those observed, then \( A < 1 \). If the plasma cools via other physical mechanisms, such as cyclotron emission cooling, then some of the total luminosity will be radiated at radio wavelengths, in which case \( A < 1 \). This has typically been set to \( A = 0.25 - 0.5 \) in previous X-ray studies\(^{20,21}\). The flux integration over the wider energy band (0.0136 - 100 keV) enabled us to constrain the increase due to unobserved flux to a factor of \( 2.2^{+1.55}_{-0.9} \), which corresponds to \( A = 0.5 - 0.4 \) and is consistent with estimates from previous studies for white dwarfs accreting from main-sequence companions, with errors corresponding to the 68% confidence interval.

The accretion rate can be inferred from the Chandra ACIS-S observations using equation (1), which describes an accretion flow converting its gravitational potential energy into an X-ray luminosity. In Extended Data Table 6 we use this equation in the limiting case, with all X-ray flux emitted within the Chandra ACIS-S passband \((A = 1)\) to transform the X-ray luminosities into accretion rates. We find the X-ray accretion rate, measured from our observations, to be \( M_X (0.3 - 7.0 \text{ keV}) = 1.63 \pm 0.4 \times 10^{-8} \text{ g s}^{-1} \). The true accretion rate could be inferred to be higher for two reasons: first, there may be additional flux carried at lower, unobserved energies, and second, there could be some contribution if the magnetic field is sufficiently high to promote some cooling via cyclotron emission cooling\(^{20}\). We have constrained the first consideration by integrating the best-fit model spectra over the full EUV and X-ray regime, finding the flux to increase by up to a factor of \( 2.2^{+1.55}_{-0.9} \), or \( A = 0.5 - 0.4 \). We will consider the possible increase in accretion rate due to cyclotron emission cooling in the following.

A magnetic field on G29–38 has the potential of funnelling the accretion flow towards the magnetic poles of the white dwarf\(^{20,21}\), and, if the density in the post-shock region is sufficiently high, cyclotron emission at radio wavelengths could contribute to its cooling, which would imply that the accretion rate based on the X-ray data is underestimated. An estimate for the temperature, \( T_X \), above which cyclotron emission cooling dominates was given by equation (10) from ref. \(^{22}\), such that one can approximate the total luminosity to be \( L_{tot} = (T_X / T_0) L_X \), where \( T_X \) is the plasma temperature with temperature \( T_0 \). The 3σ upper limit on the magnetic field of G29–38 was found to be 1.5 K from spectropolarimetry observations with FORS2 (ref. \(^{23}\)) and, even if the magnetic field of G29–38 is close to the observational detection limit, the maximum correction due to cyclotron emission cooling is predicted to be a factor of \( 1.1^{+0.1}_{-0.1} \), given the observed X-ray accretion rate (Extended Data Fig. 4). In addition, for magnetic fields less than approximately 1 K, negligible cyclotron emission cooling is predicted. In summary, compared to the X-ray accretion rate measured in the ACIS-S passband, \( M_X = 1.63 \pm 0.4 \times 10^{-8} \text{ g s}^{-1} \).
the true accretion rate could be higher by a factor of 1.1\textsuperscript{23,24} due to possible cyclotron radiation and a factor of 2.2\textsuperscript{7,25} due to additional flux emitted at unobserved wavelengths (Extended Data Table 6). Combining both possibilities for an increase in accretion rate by multiplying the two factors together, the upper estimate on the true accretion rate could be a factor of 2.4\textsuperscript{14,11} higher than the observed X-ray accretion rate, where the errors represent the 68\% confidence interval.

**Atmospheric parameters**

G29–38 was identified as a metal-polluted, hydrogen atmosphere (DAZ) white dwarf\textsuperscript{31}. It is also a pulsating, or ZZ Ceti, star with strong-amplitude non-radial pulsations with periods on the timescale \(t \approx 110–1250\) s (refs. \textsuperscript{41,44}). From fitting the broadband energy distribution\textsuperscript{45,46}, the effective temperature of G29–38 has been estimated to be \(T_{\text{eff}} = (11,529 \pm 206)\) K and \((12,090 \pm 229)\) K, when using Gaia EDR3 and PanSTARRS1 (PS1) photometry, respectively. From the Gaia EDR3 parallax, the mass was found to be \(M = (0.629 \pm 0.016)M_{\odot}\) and \((0.670 \pm 0.017)M_{\odot}\), when using Gaia EDR3 and PS1 photometry, respectively. This spans the full range of effective temperatures previously derived for this star using the spectroscopic method to fit the Balmer absorption lines\textsuperscript{15,17,28,47}. Using the observed Balmer line spectrum time-averaged over multiple pulsation cycles\textsuperscript{47} and the latest model spectra\textsuperscript{48} with 3D corrections\textsuperscript{49}, we obtain \(T_{\text{eff}} = (11,906 \pm 190)\) K and \((M = 0.689 \pm 0.031)M_{\odot}\). The accretion rate coefficients (solid lines) derived in Fig. 3 are plotted over an x-axis range to include both the EDR3 and PS1 effective temperatures, for a H-atmosphere white dwarf with a mass of \(M = 0.60M_{\odot}\). Radiation–hydrodynamic simulations of convective overshoot are currently only available for a H-atmosphere white dwarfs with surface gravities of \(log g > 8.0\) \((M_{\text{WD}} = 0.6M_{\odot})\). For self-consistency, the calculation of X-ray accretion rates (equation (1) and spectroscopic accretion rates (equation (5)) use the canonical white dwarf mass of \(M_{\text{WD}} = 0.6M_{\odot}\). This is \(3\%–15\%\) smaller than the mass of G29–38 derived from photometric and spectroscopic fits \((M_{\text{WD}} = 0.629–0.670M_{\odot})\). Given that the X-ray accretion rate scales proportionally with white dwarf mass, this represents only a small (3\%–15\%) uncertainty in the measured accretion rate.

**Spectroscopic accretion rates**

In the accretion–diffusion scenario, under the steady-state assumption, an accretion rate can be inferred from spectroscopic observations as\textsuperscript{3}\n
\[
M_i = X_i \frac{M_{\text{cxy}}}{\tau_{\text{diff},i}},
\]

where \(X_i\) is the photospheric abundance of element \(i\), \(M_{\text{cxy}}\) is the convectively mixed mass and \(\tau_{\text{diff},i}\) is the diffusion timescale set by the microscopic physics at the base of the mixed surface layers. From spectroscopic observations and model atmosphere analyses, the time-averaged accretion rate of G29–38 has previously been inferred\textsuperscript{28,29} to be \(M = (5.0 \pm 1.3) \times 10^{-5}\) and \((6.5 \pm 1.6) \times 10^{-5}\) g s\textsuperscript{-1}. The uncertainty on the first value\textsuperscript{28} was given as a typical 25\% uncertainty (0.1 dex) on the spectroscopically measured calcium abundance. The error on the second value\textsuperscript{29} was also estimated in the same way. Our observations establish an X-ray accretion rate that agrees to within a factor of 3 with previously derived spectroscopic accretion rates. The key parameters in the determination of a spectroscopic accretion rate are the observed spectroscopic metal abundance, the convectively mixed mass at the surface and the diffusion timescale at the base of the mixed region (equation (5)). Using the measured calcium abundance as a proxy for bulk Earth composition, we calculated the one-dimensional spectroscopic accretion rate with diffusion coefficients from ref. \textsuperscript{40} across the range of temperatures found in the literature for G29–38 (Fig. 3). Recent results from 3D radiation–hydrodynamic simulations predict that the convectively mixed mass can increase by up to 2.5 orders of magnitude when accounting for enhanced mixing due to convective overshoot\textsuperscript{10,12,13}, whereas the diffusion timescale can increase by up to 1.5 dex. This leads to a temperature-dependent increase in accretion rate inferred from spectroscopic observations due to convective overshoot\textsuperscript{30}. At the effective temperature of G29–38 (approximately 11,500–12,000 K), convective overshoot is predicted to increase the accretion rate by a factor of 2–4. Therefore, the 3D accretion rate is predicted to be approximately \(2 \times 10^{17}\) g s\textsuperscript{-1}, which is in close agreement with the derived X-ray accretion rate (Fig. 3).

**Data availability**

The data that support the plots within this Article and other findings of this study are available from the Chandra Data Archive. The observation ID numbers are given in Extended Data Table 1.

**Code availability**

The official Chandra reduction software package CIAO, which includes merge_obe, wavdetect and XSPEC, is freely and publicly available (cxc.cfa.harvard.edu/ciao/), as is the Python package scpy.
Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. The Pan-STARRS1 Surveys (PS1) and the PS1 public science archive have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max-Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen’s University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, the National Aeronautics and Space Administration under grant no. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation grant no. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), the Los Alamos National Laboratory and the Gordon and Betty Moore Foundation.

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Competing interests The authors declare no competing interests.

Additional information
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Extended Data Fig. 1 | Estimate of sky density from a source detection algorithm. Output of the wavdetect source detection algorithm using the recommended significance threshold, sigthresh, of $s_i = 10^{-6}$. a–c, are the results for the science bands used in this study; soft, soft + medium and broad, respectively, with 1, 2, and 3 counts shown in cyan, magenta, and white, respectively. a–c, Full field of view of the S3 chip on ACIS-S with sources identified by wavdetect shown in green. d, e, A magnified view of the vicinity near the target for the soft and soft + medium bands respectively, where the white square has sides of length 30 arcsec and is centered on the target coordinates. The source at the sky location of G29–38 is detected in the soft and soft + medium band images. The number of sources and corresponding sky density for each band can be found in Extended Data Table 3. f, Broadband (0.5–7.0 keV) events recorded near the sky position of the only Gaia source (EDR3 source ID: 266110815469507072) in the full CCD image which has a detected X-ray source in the broadband image within 5 arcsec. The output of wavdetect gives the coordinates for the center of the detected source in (RA, DEC) as $(352.182358 \pm 0.000022, +5.341529 \pm 0.000020)$, shown in the figure with a cyan cross. The coordinates of the Gaia EDR3 source, corrected for proper motion, are $(352.18248533 \pm 0.00000007, +5.34150200 \pm 0.00000098)$, indicated in the figure with a white cross. The Chandra source is offset compared to the expected Gaia position by $(-0.46 \pm 0.08, 0.10 \pm 0.07)$, which is consistent with the offset of our target from the expected position (see Fig. 2).
Extended Data Fig. 2 | Monte Carlo aperture photometry. a, c, The blue points show the positions of the approximately 100,000 test apertures, each 1 arcsec in radius, used to sample 100 arcsec around the target. The absolute number of test apertures, after removing those that fell within a masked region, is shown in the panels. The sky coordinates of all recorded events that fall within a masked region are shown in orange. b, d, The normalized histogram shows the fraction of test apertures with event counts equal to or greater than that of a given bin. The Monte Carlo was performed on the soft (a, b) and soft + medium (c, d) bands. The soft band analysis has 0.001% of test apertures returning four counts, enabling us to rule out chance alignment at 4.4σ.
Extended Data Fig. 3 | See next page for caption.
Extended Data Fig. 3 | Spectral modelling of observed X-ray events.

a, Bottom, in units of instrumental counts we show the five recorded events (black) and six best-fit spectral models assuming Solar\textsuperscript{39} (magenta), bulk Earth\textsuperscript{40} (blue) and photospheric\textsuperscript{17} (red) abundances, with either the vvapec isothermal (solid) and mkcflow cooling flow (dotted) plasma models. We also indicate the dominant metal emission lines (O, Mg, Si and Fe) from the isothermal, photospheric abundance model. Middle, in real flux units, we show the synthetic spectra for the photospheric abundances with the isothermal (solid) and cooling flow (dotted) plasma models. The modelling suggests the most likely origin of the source photon at 1.3 keV was a Mg transition. Top, the effective area of the ACIS-S detector is shown in green, hatch. The absence of harder X-ray events (>2.0 keV) in the Chandra observations demonstrates that the plasma emission spectrum is very soft.

b, Spectral energy distribution of the best-fit isothermal (blue) and cooling flow (orange) plasma models with bulk Earth abundances down to the extreme ultraviolet (EUV) energy regime. Also shown are the standard Chandra science bands: soft, medium and hard. Both models provide a convergent fit within the Chandra ACIS-S passband, but the cooling flow provides a more physical and larger estimate of the lower-energy flux.

c, The X-ray flux measured in 3 bands: 0.5–7.0 keV, 0.3–7.0 keV and 0.0136–100 keV, using the cooling flow model for the photospheric abundances\textsuperscript{17} is shown in open diamonds. The filled horizontal bands show the 68% and 90% confidence intervals on the X-ray accretion rate, which is computed using Equation (1). The X-ray accretion rates are computed using Equation (1), with $A = 1$, $R_{WD} = 0.0129 R_{\odot}$, and $M_{WD} = 0.6 M_{\odot}$. The spectroscopic accretion rates (solid lines) are the same as shown in Fig. 3, with the 1σ uncertainty shown with dashed lines. Also shown in solid circles (blue and orange) are the previously published inferred accretion rates for G29–38, based on photospheric abundances from spectroscopic observations\textsuperscript{27,28}. 

Extended Data Fig. 4 | Limit on cyclotron emission cooling as source of additional luminosity. 

**a.** An estimate for the total luminosity from the measured X-ray luminosity, accounting for cyclotron emission cooling. We compare the measured plasma temperature, $k_B T_X = (0.61 \pm 0.28) \text{ keV}$, given by the cooling flow model and photospheric abundances, with the critical plasma temperature, $T_B$, above which cyclotron emission cooling dominates, defined by equation 10 from ref. 22. The authors provide the ratio $T_L/T_X \approx T_B$ as an estimate of, for a range of accretion rates and global magnetic field strengths, the predicted increase in total luminosity compared to X-ray luminosity if the plasma temperature is sufficient to be dominated by cyclotron emission cooling. The horizontal dotted line indicates $T_X/T_B = 1$, where no correction is expected below this. The vertical dotted line indicates the 3σ upper limit on the magnetic field strength from FORS2 spectropolarimetric observations. The solid lines indicate the increase in total luminosity when compared to the observed X-ray luminosity. 

**b.** Predicted additional luminosity for an assumed global magnetic field at the 3σ limit (1.5 kG) across the full range of plasma temperatures and accretion rates calculated in this work (see Extended Data Tables 5 & 6). White space indicates no additional luminosity. The upper plasma temperature from the cooling flow model and accretion rate derived from the isothermal plasma model is shown (solid) along with the 68% uncertainty (dashed). Even at the observational upper limit, the predicted increase due to cyclotron emission cooling is a factor of $1.1_{-0.1}^{+0.6}$. 
### Extended Data Table 1 | Chandra observations of G29–38

| Obs ID | Instrument | Exposure Time (ks) | Start Date (yyyymm-dd) | Epoch (yr) |
|--------|------------|--------------------|------------------------|------------|
| 24257  | ACIS-S     | 24.58              | 2020-09-22             | J2020.727  |
| 24256  | ACIS-S     | 14.89              | 2020-09-24             | J2020.732  |
| 24658  | ACIS-S     | 14.89              | 2020-09-24             | J2020.732  |
| 23379  | ACIS-S     | 26.23              | 2020-09-26             | J2020.738  |
| 24657  | ACIS-S     | 25.74              | 2020-09-27             | J2020.740  |
| Total: | –          | 106.33             | –                      | –          |

Details of Chandra observations carried out between 22 and 27 September 2020 with G29-28 as the target (PI: Cunningham).
### Extended Data Table 2 | Statistical significance of source detection

| Band        | Energy (keV) | Source (per ap.) | Background (per ap.) | CL (%) | Significance (σ) |
|-------------|--------------|------------------|----------------------|--------|------------------|
|             |              |                  |                      |        |                  |
|             |              |                  |                      |        |                  |
| Soft        | 0.5–1.2      | 4                | 0.100                | 99.99962 | 99.9999984 | 4.62 | 5.65 |
| Soft+Medium | 0.5–2.0      | 5                | 0.205                | 99.99975 | 99.999997 | 4.71 | 5.94 |
| Broad       | 0.5–7.0      | 5                | 0.566                | 99.97255 | 99.9999590 | 3.64 | 5.06 |

Source counts \( N \) and expected background \( b \) in the three standard ACIS energy bands used in this study, given in units of counts per 1 arcsec aperture \( r_{\text{ap}} \). From top to bottom, the total background counts in each band was \( N_b = 270, 555 \) and 1530 (in the 52 arcsec radius background region). The expected background in the 1 arcsec radius source region was thus computed as \( b = N_b / 52^2 \). This includes reprocessing using the VFAINT mode for background cleaning. For an expected background \( b \), the Poisson distribution gives the probability of receiving \( N \) or more counts as \( P(N|b) = b^{N} e^{-b} / N! \). We therefore reject the null hypothesis of detecting no source photons with a confidence of \( CL = 100 \times (1 - P(N|b)) \). We also provide results for the relocalized 0.5 arcsec aperture \( r_{0.5} \), and note that the source counts are the same for both aperture sizes.
### Extended Data Table 3 | Sky density of sources from the wavdetect source detection algorithm

| Band       | No. Sources | Target? | Sky Density $\left(10^{-5} \text{ arcsec}^{-2}\right)$ | CL$_{\text{align}}$ (%) | Significance ($\sigma$) |
|------------|-------------|---------|----------------------------------------------------|-------------------------|-------------------------|
|            | $s_1$ | $s_2$ | $s_1$ | $s_2$ | $s_1$ | $s_1$ |
| Soft       | 7     | 6     | ✓     | ×     | 2.36  | 2.36  | 99.996  | 4.1 |
| Soft+Medium| 25    | 23    | ✓     | ✓     | 9.46  | 8.76  | 99.985  | 3.8 |
| Broad      | 32    | 32    | ×     | ×     | 12.6  | 12.6  | 99.979  | 3.7 |

We present results in each of the three standard science bands considered (soft, soft + medium and broad), for two values of the significance threshold parameter, sigthresh, where $s_1$ and $s_2$ are significance thresholds of $1 \times 10^{-6}$ and $5 \times 10^{-7}$. From the documentation, the significance threshold should be set to $s_1 = 1/n_p$, which typically produces one false detection. The ACIS-S S3 CCD has 1024 x 1024 pixels, so $s_1$ should be a sufficiently low threshold. However, to align with the world coordinate system (WCS), the CCD image is rotated relative to the bounding box of the image, meaning that the image on which wavdetect was run has 1414 x 1401 pixels, hence the value of $s_2 = 1/(1414 \times 1401) = 5 \times 10^{-7}$. The sky density is computed as the number of sources (excluding the target, if detected), divided by the field of view, which is estimated as $(1024^2 \times 0.4920^2)$, where the second number is the pixel size in arcsec. Multiplying the sky density by the area defined by the 90% confidence limit on the radial offset of ACIS-S targets ($0.72^2$ arcsec$^2$), we provide the confidence, CL$_{\text{align}}$, with which we can reject the hypothesis that our source counts could originate from a background source.
Extended Data Table 4 | Confidence interval on Chandra ACIS-S count rate

| Band       | Energy (keV) | Count rate (ap. $^{-1}$ ks$^{-1}$) | 68%         | 90%         |
|------------|--------------|------------------------------------|-------------|-------------|
|            | Source       | Background                         | low         | high        | low         | high        |
| Soft       | 0.5–1.2      | 0.038                              | 0.0010      | 0.021       | 0.059       | 0.013       | 0.078       |
| Soft+Medium| 0.5–2.0      | 0.047                              | 0.0021      | 0.027       | 0.070       | 0.018       | 0.090       |
| Broad      | 0.5–7.0      | 0.047                              | 0.0057      | 0.024       | 0.066       | 0.015       | 0.086       |

The 68% and 90% confidence intervals for the source counts (N) given in Extended Data Table 2, which have been converted to a count rate using the 106.33 ks total exposure time for the three standard Chandra energy bands used in this study. Confidence intervals are calculated using the method of ref. 34, which is a Bayesian approach to Poisson statistics in the presence of a background that uses a simple prior on the number of source counts not being negative. All count rate values are given in units of counts per ks, per 1 arcsec aperture.
The 68% and 90% confidence intervals for the derived plasma temperature are based on fits to the full ACIS-S spectrum (plotted in Extended Data Figure 3). Best fits and confidence intervals were determined using the C-statistic\(^4\), and with no background subtraction. For the cooling flow model these are the upper temperature of a range of temperatures extending down to 0.08 keV, with the emission measure at each temperature weighted by the inverse of the emissivity.
### Extended Data Table 6 | Best-fit X-ray properties of G29–38

| X-ray measurement   | Energy (keV) | Best-fit | 68%      | 90%      |
|---------------------|--------------|----------|----------|----------|
|                     |              | low | high | low | high |
| Flux \((10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2})\) | 0.5–7.0 | **1.78** | 1.40 | 2.53 | 1.20 | 4.53 |
|                     | 0.3–7.0 | **1.97** | 1.49 | 3.52 | 1.26 | 9.40 |
|                     | 0.0136–100 | **4.34** | 2.62 | 19.1 | 2.09 | 218.0 |
| Luminosity \((10^{25} \text{ erg s}^{-1})\) | 0.5–7.0 | **6.54** | 5.15 | 9.30 | 4.41 | 16.7 |
|                     | 0.3–7.0 | **7.24** | 5.48 | 12.9 | 4.63 | 34.5 |
|                     | 0.0136–100 | **16.0** | 9.63 | 70.2 | 7.68 | 801.3 |
| Accretion rate \((10^9 \text{ g s}^{-1})\) | 0.5–7.0 | **1.48** | 1.16 | 2.09 | 1.00 | 3.76 |
|                     | 0.3–7.0 | **1.63** | 1.23 | 2.92 | 1.05 | 7.80 |
|                     | 0.0136–100 | **3.60** | 2.17 | 15.8 | 1.73 | 181 |

The best-fit fluxes are computed across three spectral energy ranges using the cooling flow model with photospheric abundances\(^{17}\). The first two energy ranges are within the wavelength range of our observations and provide a robust lower limit on the flux. The third, wider energy band allows for more flux to be carried at higher and lower energies, thus providing an upper estimate of the X-ray flux based on our observations. The 68% and 90% confidence intervals for the derived flux based on those for the plasma temperature in Extended Data Table 5. From the fluxes \(F_X\), the best-fit X-ray luminosity \(L_X\) was derived using \(L_X = 4\pi d^2 F_X\). The best-fit X-ray accretion rate \(M_X\) derived using \(M_X = 2\mu R_{\text{WD}}/(GM_{\text{WD}})\).