

Stratified wind from a super-Eddington X-ray binary is slower than expected

XRISM collaboration*

Accretion discs in strong gravity ubiquitously produce winds, seen as blueshifted absorption lines in the X-ray band of both stellar mass X-ray binaries (black holes and neutron stars)^{1–4} and supermassive black holes⁵. Some of the most powerful winds (termed Eddington winds) are expected to arise from systems where radiation pressure is sufficient to unbind material from the inner disc ($L \gtrsim L_{\text{Edd}}$). These should be extremely fast and carry a large amount of kinetic power, which, when associated with supermassive black holes, would make them a prime contender for the feedback mechanism linking the growth of those black holes with their host galaxies⁶. Here we show the first XRISM Resolve spectrum of the Galactic neutron star X-ray binary, GX 13+1, which reveals in exquisite detail one of the densest winds ever seen in absorption lines. This Compton-thick wind significantly attenuates the flux, making it appear faint while it is intrinsically more luminous than usual ($L \gtrsim L_{\text{Edd}}$). However, the wind is extremely slow, more consistent with the predictions of thermal-radiative winds launched by X-ray irradiation of the outer disc than with the expected Eddington wind driven by radiation pressure from the inner disc. This puts new constraints on the origin of winds from bright accretion flows in binaries, but also highlights the very different origin required for the ultrafast ($v \sim 0.3c$) winds seen in recent Resolve observations of a supermassive black hole at similarly high Eddington ratio⁷.

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GX 13+1 is a disk-accreting neutron star in a 24.5-day orbit^{8,9} with a giant (K5 III) companion star¹⁰, which gives a large mass transfer rate through the Roche lobe¹¹, resulting in a persistently bright X-ray source ($L \sim 0.5L_{\text{Edd}}$ for a $1.4M_{\odot}$ neutron star at a distance of 7 kpc¹⁰). The presence of dips in the X-ray lightcurve indicates a high binary inclination¹², which is optimal for observations of accretion disc winds^{1,13,14}. Indeed, every X-ray observation of GX 13+1 with sufficient spectral resolution has revealed blueshifted absorption lines^{15–18}, making it an ideal target for Resolve, an X-ray micro-calorimeter onboard the new JAXA/NASA/ESA mission *XRISM*¹⁹. Resolve has an energy resolution of 4.5 eV at 6 keV, which is a factor 4 better than the previous state of the art for bright binaries (third order data²⁰ from the High-Energy Transmission Grating Spectrometer²¹, hereafter HETGS), and with much larger effective area, especially above 7 keV. The combination of improved resolution and larger area enables more sensitive measurements of the velocity and ionisation structure of accretion disc winds, critical for diagnosing the physical properties and launch mechanisms of these outflows²².

The new data on GX 13+1 from Resolve were taken on 25 February 2024; more details of the observations and data analysis are given in Methods. The Resolve spectrum, shown in Figure 1, reveals dozens of strong, slightly blueshifted ($v_{\text{out}} \sim 330$ km/s), narrow ($v_{\text{turb}} \sim 150$ km/s) X-ray absorption lines. Most of these are from H-like and He-like ions, of multiple elements (Si, S, Ar, Ca, Ti, Cr, Mn, Fe, Co, Ni), indicating a highly ionised absorber.

Many of the lines below 7 keV (Figure 1a,b) have been studied before, though at lower resolution and signal-to-noise, in *Chandra* HETGS observations of this source¹⁸. What is completely

new is the number and depth of lines above 7 keV (Figure 1c), with multiple higher order transitions detected out to at least $K\theta$ ($n = 1 - 9$) for Fe XXV and $K\eta$ ($n = 1 - 8$) for Fe XXVI. These lines have small oscillator strengths, so their depth requires the column density of the wind to be extremely high, both in an absolute sense and in comparison to the prior *Chandra* observations (see below).

We first model the absorption lines from each ion separately, and find that these are consistent with being produced by a single absorber with ionisation parameter $\log \xi \sim 3.9$ and an equivalent column density of $N_{\text{H}} \sim 1.3 - 1.4 \times 10^{24} \text{ cm}^{-2}$, assuming solar abundances. We confirm this by modelling all the ions together using the photoionisation code PION^{23,24} (see Methods). The derived column is so large that the wind is optically thick to electron scattering, with $\tau_{es} \sim 1$. This significantly attenuates the radiation from the central X-ray source as it passes through the wind, reducing the direct continuum flux by a geometry-dependent factor $\sim \exp(\tau_{es}) \sim 3$. Correcting for this effect, we infer a bolometric luminosity of $L = 1.8 \times 10^{38} \text{ erg s}^{-1}$, which is $\sim L_{\text{Edd}}$: this Compton-thick wind is produced by a source radiating at the Eddington limit.

Both these conclusions were initially surprising, as the ionised winds seen in previous observations of GX 13+1 with the *Chandra* HETGS had large but optically thin column densities^{15,18} of $N_{\text{H}} \sim 2 - 3 \times 10^{23} \text{ cm}^{-2}$, from a source with large but sub-Eddington luminosities of $\sim 0.5 L_{\text{Edd}}$. The unusual behavior of GX13+1 during our observation is very clearly illustrated by our simultaneous *NuSTAR* broadband X-ray data (see Methods). These are shown as the orange points in Figure 2, where we also show a prior archival *NuSTAR* spectrum (green). GX13+1 is noticeably

fainter during our observation and has a much stronger absorption feature at ~ 8.8 keV, i.e., at the K-edge of Fe XXV. The column density in this ion is plainly much larger than in the majority of archival data. Other archival broadband datasets²⁵ (RXTE: grey) confirm that this “reduced flux/strong Fe XXV edge” state is very unusual ($\lesssim 10\%$ of observations), but lack the energy resolution to unambiguously connect this behavior to attenuation in a high-column wind.

Correcting our best-fit continuum model for electron scattering attenuation in the slow wind gives an intrinsic flux shown as the lower edge of the blue band in Figure 2, implying the source is intrinsically more luminous than normal. We suggest a causal relationship: an increase in the intrinsic X-ray luminosity enhances the wind to such an extent that it becomes Compton-thick, suppressing the observed flux and making the source appear dimmer (but with strong wind signatures). The increase in wind column may also explain the different X-ray polarisation properties seen by IXPE during the *XRISM* observation²⁶.

The optically thick column in the slow wind in GX 13+1 is actually only part of the material obscuring the source. Figure 3 shows a detailed view of the strongest lines, the Fe XXV $K\alpha$ intercombination ($x + y : 6.670$ keV) and resonance ($w : 6.700$ keV) transitions, and the Fe XXVI $Ly\alpha_{1,2}$ fine structure doublet. The blue line shows the predicted absorption line profiles using the column and velocities derived above for the slow wind, assuming that this covers all of the intrinsic X-ray emission region(s). It is immediately apparent that the model predicts that the narrow cores of these strong lines should be completely black (opaque) at their centres, whereas the data unambiguously show residual flux. This shows there must be an additional source of X-rays

that is not absorbed by the wind, most likely the wind itself, which scatters and re-radiates some of the X-rays from the central source, forming a diffuse secondary source of X-rays. The comparison also clearly reveals that the single velocity absorption model misses the blue (higher-energy) wing seen especially on the Fe XXVI Ly α_1 absorption line at ~ 7 keV, indicating the presence of higher velocity material. This most likely indicates that the wind is somewhat stratified, with the most highly ionised material having speeds that are roughly twice that of the slower, less ionised material that forms the narrow line core.

Our final model incorporates all these components. We use two absorption zones: a slow absorber to match the bulk of the material, and a faster column to match the blue wing on the most highly ionised lines. The model also includes the line and recombination emission calculated by the photoionisation code for these two absorption columns to approximate the reprocessed emission from the wind. These emission components are assumed to be at rest but velocity broadened, as expected for emission over all azimuths, and are partially absorbed to approximate the multiple sightlines (see Figure 4). We also include an additional diffuse component from electron scattering of the intrinsic continuum. This is the model (orange) shown with the data in Figure 1, and Figure 3, with full fit parameters in Methods (Extended Data Table 2).

The faster wind column density is difficult to robustly constrain. Most of the elements are fully ionised so there is a large and model-dependent correction between the observed blue wing and the total column. For example, at our best fit ($\log \xi = 4.69 \pm 0.01$), only 10% of Fe is visible as Fe XXVI; all remaining Fe is completely ionised (see Methods, Extended Data Figure 5). The

fast wind in our best fit model has a column density of $N_{\text{H}} = (0.79 \pm 0.09) \times 10^{24} \text{ cm}^{-2}$, increasing the line-of-sight optical depth to $\tau_{es} \sim 1.8$. Correcting for this attenuation results in an even higher estimate for the intrinsic luminosity of $L \sim 1.8L_{\text{Edd}}$, giving the upper limit of the band of likely intrinsic fluxes shown in blue in Figure 2.

The two wind components are most likely an approximation of a continuous wind structure as they have similar kinematics. The inner face of the wind (smallest radii) is more highly illuminated and faster, slightly shielding the less ionised, slower material at larger radii. This assumed geometry allows us to estimate the physical parameters of the outflow (see Methods). The wind is launched from $R_{\text{f}} \sim 3 \times 10^4 R_{\text{g}}$ ($6 \times 10^9 \text{ cm}$), with initial density $\sim 10^{14} \text{ cm}^{-3}$ for a source of intrinsic luminosity $1.8L_{\text{Edd}}$. Attenuation by electron scattering reduces the flux to $\sim L_{\text{Edd}}$ by $R_{\text{s}} \sim 7 \times 10^4 R_{\text{g}}$ ($1.5 \times 10^{10} \text{ cm}$), beyond which the wind is slower. This is shown schematically in Figure 4.

We can estimate the mass loss rate of the wind if we can independently estimate the solid angle, Ω subtended by the wind. For optically thin winds this can be determined from the contribution of scattered emission to the total flux as $f_{\text{scatt}} \approx (\Omega/4\pi)(1 - e^{-\tau_{es}})$. The observed scattered fraction is difficult to robustly constrain as it depends on the details of how the diffuse flux is modelled. In our fits it ranges from $0.22 - 0.04$ (compare Methods: Extended Data Tables 1 and 2). We assume these numbers bracket the true scattered flux, so $0.04 < (\Omega/4\pi) < 0.22$. The assumed mass profile gives a larger uncertainty, and both together give a range in total (fast plus slow) mass loss rate of $1.2 < \dot{M}_{18} < 39$, where \dot{M}_{18} units of 10^{18} g s^{-1} (see Methods). This is $\sim 0.3 - 10 \times$

the inferred mass accretion rate onto the neutron star; such highly non-conservative mass transfer, with as much or more mass being ejected from the system than is accreting, is often seen in galactic binary disc winds^{27,28}. Nonetheless, the kinetic power in this wind is very much smaller than the radiative power, as its velocity (even with the faster component) $\ll c$.

Similarly high column winds were suggested to explain rare observations of BHB with potentially similar properties (near-Eddington or super-Eddington flux, large disc, high inclination^{29–32}). However, without both (1) broadband spectra to show the edge depth as in Figure 2 and (2) sensitive high-resolution spectra above 7 keV to reveal unsaturated high-order lines (Figure 1, lower panel), it is difficult to distinguish between an intrinsically dim source with an optically thin wind ($N_{\text{H}} \sim \text{few} \times 10^{23} \text{ cm}^{-2}$) and a source that is much brighter but strongly attenuated by an optically thick wind.

Accretion disc winds in X-ray binaries are often viewed as small-scale versions of the winds from supermassive black holes that drive much of AGN feedback: whether these winds are launched by magnetic fields, radiation pressure, or Compton heating remains an open question across the mass scale^{1–4}. The *XRISM* observation of GX 13+1 provides one of the most sensitive probes of the physics of accretion disc winds to date. We therefore consider the origin of this wind by comparing to expectations for winds from all of these driving mechanisms.

The source is at or above the Eddington limit, meaning that radiation from within the disc is strong enough to directly launch its own photosphere as a wind. For $L \sim 1 - 2L_{\text{Edd}}$ this occurs only in the inner disc, where the local flux peaks. This “Eddington wind” should be fast, with

mildly relativistic velocities $v_{\text{out}} \sim 0.2 c$ (e.g. ref.³³), not at all compatible with the observed wind in GX 13+1.

Instead, radiation pressure from the central source could launch a wind by illuminating material at any other radius in the disc, as the effective gravity is proportional to $(1 - L/L_{\text{Edd}})$ (ref.^{34,35}). However, this illumination also heats the disc surface to the radiation temperature; in a sub-Eddington source this heating alone can be sufficient to drive a wind from radii where the sound speed exceeds the local escape velocity (thermal/Compton heated winds)^{35–37}. Radiation pressure acts as a boost to the velocity for $L > 0.2L_{\text{Edd}}$ (thermal-radiative winds)^{38,39}.

Thermal-radiative driving can give a fairly good match to most previous data on binary winds^{2,18,40,41}, but in their simplest form these models predict narrow lines, as all the material is heated to the same temperature so expands with constant velocity⁴². However, detailed radiation hydrodynamical simulations of thermal-radiative winds from large accretion discs show that these winds do start to become stratified at high luminosities ($L = 0.5 - 0.7L_{\text{Edd}}$) due to optical depth effects. These more realistic simulations of thermal-radiative winds have faster, higher ionisation material on the inner, more strongly illuminated face of the wind, with velocities closely matched to those seen in GX 13+1^{28,42,43} (see also refs^{44,45}). However, the predicted column densities along the line of sight are only a few $\times 10^{23} \text{ cm}^{-2}$, a factor 10 below those required here. Part of this discrepancy is almost certainly that the simulations do not extend to super-Eddington luminosities, but an additional problem is that current codes do not yet include scattered emission from the wind in calculating the illumination of the disc to launch the wind. This scattered flux can exceed the

direct illumination when the wind becomes optically thick⁴⁶.

Alternatively, magnetic winds can also give a stratified velocity/ionisation structure. The drawback of this driving mechanism is that the magnetic field configuration (and consequent wind density) cannot currently be predicted from first principles, but assuming self-similar, large scale fields connecting into the disc at all radii^{47,48}, gives a wind density structure $n(R) \propto R^{-p}$ with $p = 1 - 1.5$ (ref.^{49,50}). This predicts that material launched at smaller radii has faster velocity and higher ionisation state, generically producing blueward asymmetric line profiles, as observed in the FeXXVI Ly α_1 line (see Figure 3). However, this self-similar model is problematic for GX 13+1 as it predicts an additional optical depth of $\tau_{\text{es}} \sim 6$ in fully-ionised material inwards of the fast component. This would require an uncomfortably large intrinsic source luminosity to produce the observed X-ray flux.

Whatever the physical origin, the observed slow wind can be used to put upper limits on the kinetic power of any fast wind from the inner disc along this line of sight, such as a radiation pressure driven wind from the inner, bright $L \gtrsim L_{\text{Edd}}$ flow. Such winds have predicted velocities $v \sim 0.1 - 0.2c$ and kinetic power of $\sim 0.05L_{\text{Edd}}$ in both analytic and numerical simulations⁵¹⁻⁵³, but such high ram pressure material along our sight line would strongly disrupt the slow, quiet kinematics of the observed outer disc wind. Our data require that any fast, wind produced by the $L \sim L_{\text{Edd}}$ inner disc regions must be somewhat collimated in the polar direction, potentially by formation of an inner disc funnel.

This is important as fast, inner disc winds with $v \sim 0.2c$ are seen in supermassive black

holes, most compellingly from those with $L \gtrsim L_{\text{Edd}}$ (e.g. PDS456⁵). This AGN wind was spectacularly confirmed by recent *XRISM* data, where the strong emission as well as absorption signatures require that the wind is quasi-spherical⁷, unlike any inner disc wind in GX 13+1. Understanding this difference in inner disc and wind properties across the mass scale will lead to a deeper understanding of the physics of AGN feedback across cosmic time.

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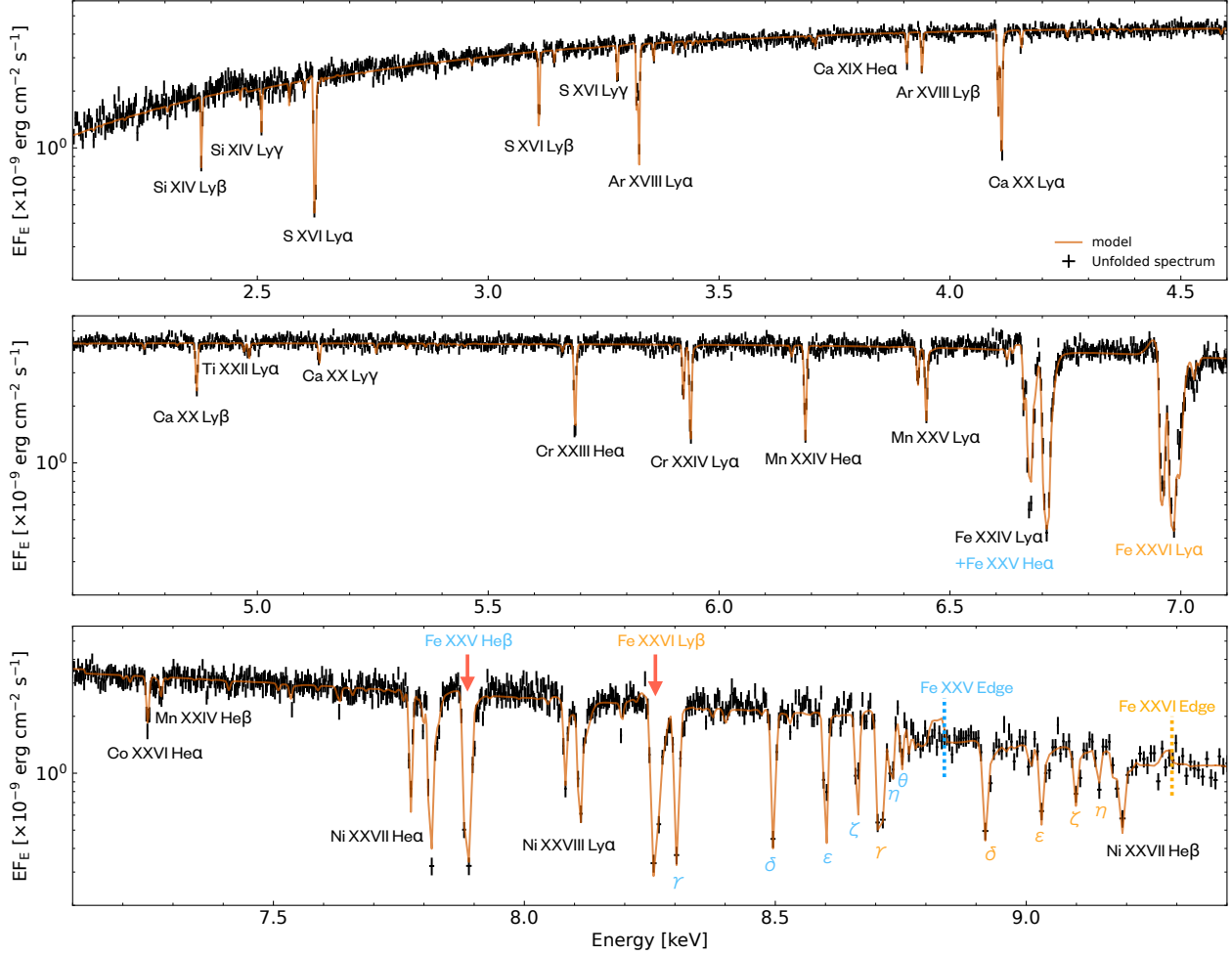


Fig. 1: The Resolve/XRISM spectrum of GX 13+1. This is dominated by multiple absorption lines from H- and He-like ions, blueshifted by ~ 330 km/s. All the fine structure transitions in these lines are resolved, showing that the lines are very narrow (velocity dispersion ~ 150 km/s). All strong lines are labelled; the $1 - n$ transitions of Fe XXV and Fe XXVI are indicated in cyan and orange, respectively. Even the weakest line identified here (Ti XXII $\text{Ly}\alpha_{1,2}$ around 4.95 keV) is highly significantly detected ($\Delta\chi^2 = 32$ for 1 additional degree of freedom). The orange line shows the best fit model described in the text, with an intrinsic continuum absorbed by the slow wind, but with a faster (700km/s), broader (300km/s) even more highly ionised component to fit the blue wing seen in Fe XXVI $\text{Ly}\alpha_{1,2}$ (see Figure 3). The model also includes diffuse emission from the wind (modelled using scattered intrinsic flux plus photoionised line and recombination continua from both wind components, all with some self absorption in the wind). This fits the data fairly well overall (see Methods, Extended Data Table 2), except around the FeXXV (8.8 keV) and FeXXVI (9.25 keV) edges where the photoionisation model used here is incomplete (only including transitions up to $n = 16$). The total electron scattering optical depth in the slow(both) winds is $\tau_{\text{es}} \sim 1(1.8)$, attenuating the intrinsic flux (see Figure 2).

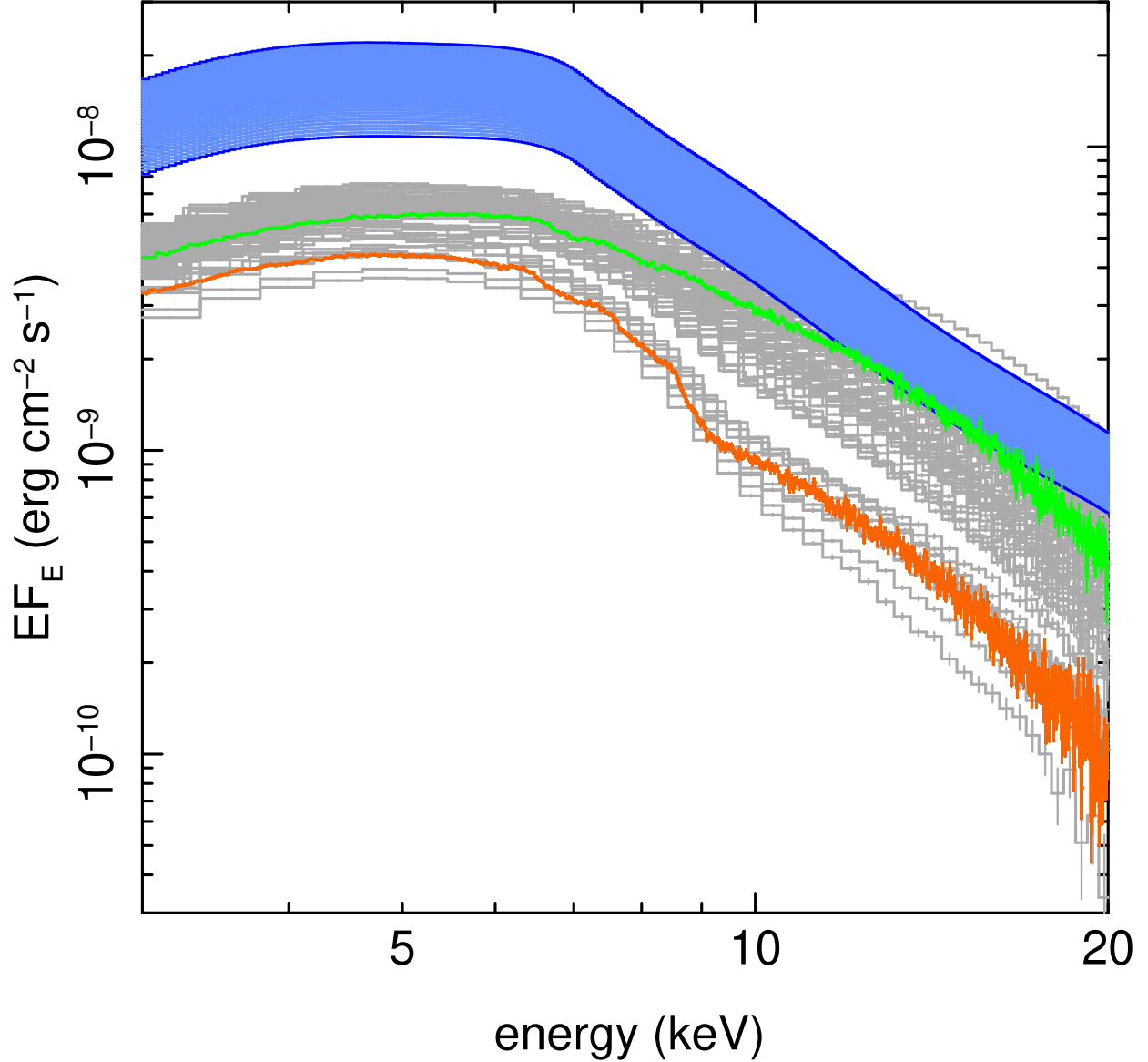


Fig. 2: Historical X-ray variability of GX 13+1. The archival *NuSTAR* spectrum of GX 13+1 (green) is similar to most of the archival *RXTE* data (grey). Instead, the *XRISM*-coordinated *NuSTAR* spectrum (orange) has lower flux and shows a much deeper K edge from Fe XXV at 8.8 keV. On closer inspection, 5-10% of the archival *RXTE* spectra are similar to this recent *NuSTAR* observation, indicating that this dense wind/super-Eddington phase is recurring in the source. The blue band shows a range of possible continuum spectra of GX 13+1 after correcting for attenuation due to electron scattering in the wind. The lower end of the envelope corresponds to $\tau_{\text{es}} = 1$ from the slow wind alone, while the upper end corresponds to $\tau_{\text{es}} = 1.8$ as inferred from the best fit model for the slow plus fast wind. The source is intrinsically more luminous than normal, at or above Eddington.

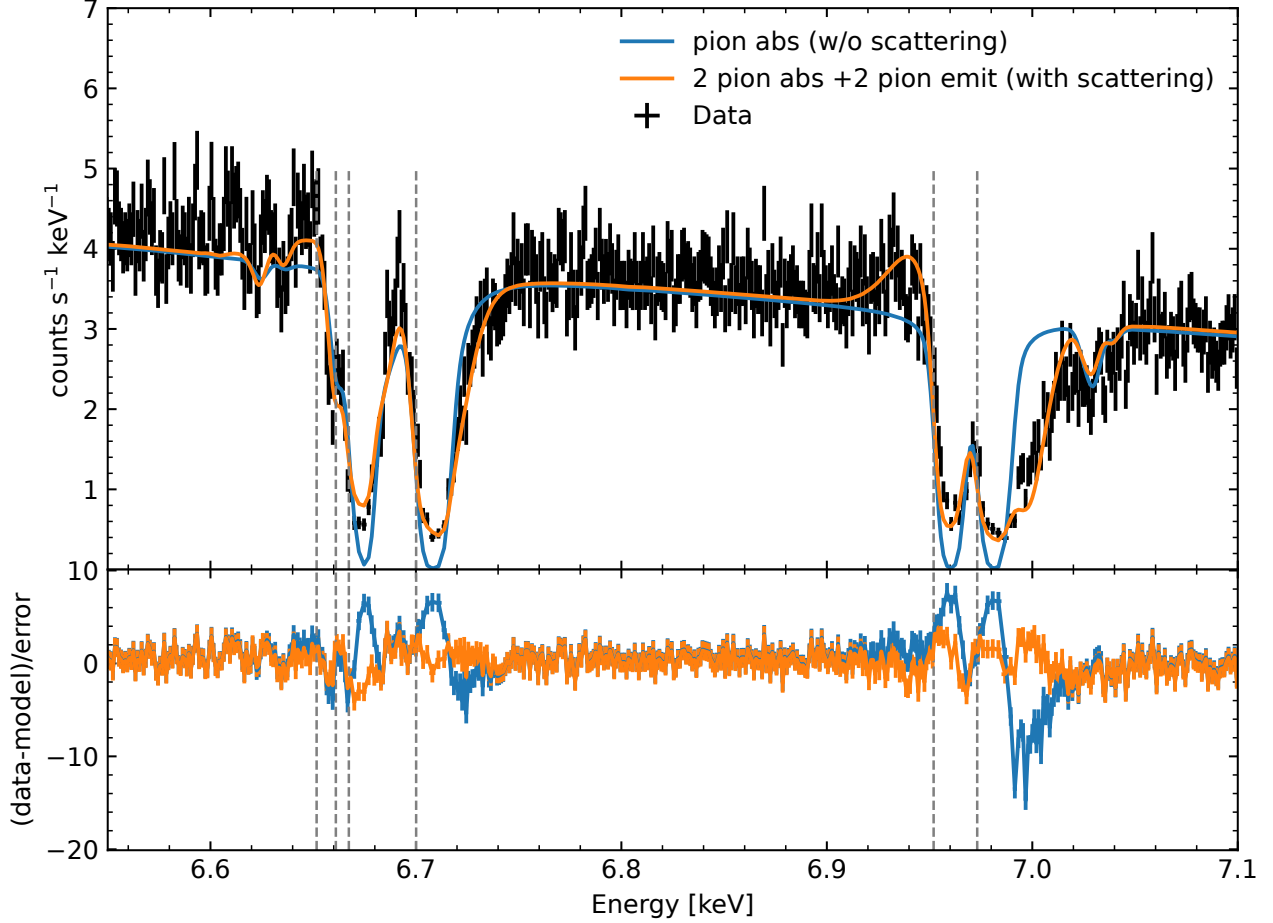


Fig. 3: Zoom in around the Fe $K\alpha$ lines. The dashed vertical lines show the restframe energies of (from left to right) the weak Fe XXIV doublet (6.652 and 6.661 keV), Fe XXV (intercombination: 6.667 and resonance: 6.700 keV) and the Fe XXVI doublet (6.952 and 6.973 keV). The blue line shows a single photoionised absorption model with parameters which fit the multiple narrow lines in the rest of the spectrum. This predicts that the lines go black in their centres, but the data show residual emission due to the presence of diffuse flux (most likely reprocessing and scattering from the wind itself). It also misses the blue wing in the Fe XXVI $Ly\alpha_{1,2}$ absorption line at 7 keV, showing that there is higher velocity material at higher ionisation state. The orange line shows our best model including these additional components in both absorption and emission.

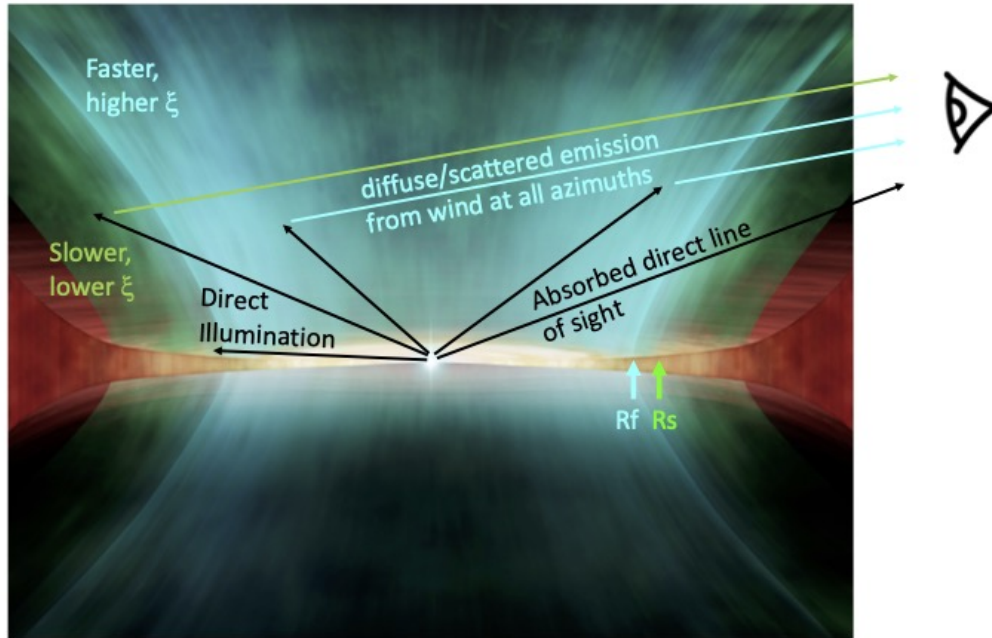


Fig. 4: Artist's impression of the wind in GX 13+1 as seen by *XRISM*. The bulk of the wind (green) is optically thick, highly ionised and slow but it has a faster, even more highly ionised skin on its inner edge (blue). We see the central source directly through this heavy absorption, but the irradiated wind material forms a secondary source of diffuse X-rays from scattering and re-emission which can be seen along multiple paths. Credit: CfA/Melissa Weiss

Acknowledgments This work was supported by JSPS KAKENHI grant numbers JP24KJ0152, JP22H00158, JP22H01268, JP22K03624, JP23H04899, JP21K13963, JP24K00638, JP24K17105, JP21K13958, JP21H01095, JP23K20850, JP24H00253, JP21K03615, JP24K00677, JP20K14491, JP23H00151, JP19K21884, JP20H01947, JP20KK0071, JP23K20239, JP24K00672, JP24K17104, JP24K17093, JP20K04009, JP21H04493, JP20H01946, JP23K13154, JP19K14762, JP20H05857, JP23H01211, JP23K03454, JP23K22548, JP23K03459, JP21H04493 and NASA grant numbers 80NSSC24K1148, 80NSSC24K1774, 80NSSC18K0978, 80NSSC20K0883, 80NSSC20K0737, 80NSSC24K0678, 80NSSC18K1684, 80NSSC25K7064, 80NSSC23K0995, 80NSSC18K0988, 80NSSC23K1656 and 80NSSC23K0684. CD acknowledges support from STFC through grant ST/T000244/1 and a Leverhulme Trust International Fellowship IF-2024-020. LC acknowledges support from NSF award 2205918. The material is based upon work supported by NASA under award number 80GSFC21M0002. This work was supported by the JSPS Core-to-Core Program, JPJSCCA20220002. MM is supported by Yamada Science Foundation. LG acknowledges financial support from Canadian Space Agency grant 18XARMSTMA. AT is supported in part by the Kagoshima University postdoctoral research program (KU-DREAM). SY acknowledges support by the RIKEN SPDR Program. IZ acknowledges partial support from the Alfred P. Sloan Foundation through the Sloan Research Fellowship. Part of this work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. The material is based on work supported by the Strategic Research Center of Saitama University.

Author contributions RT led the analysis, CD led the GX13+1 XRISM team. CD and JN were responsible for the manuscript writing. MM, FSP and SY led the XRISM Resolve data extraction, RT led the *NuSTAR* data, JN led the photoionisation code comparisons. The GX13+1 XRISM team (AK, EB, EC, MS, MDT, JN, HT, SY, LC, RS, KY, TD) contributed equally to reading and commenting on the manuscript.

Competing interests The authors declare no competing interests

Data availability The *XRISM* Resolve data will be publicly available in the archives after the proprietary period ends. The *NuSTAR* dataset (ObsID 30901010002) is already publicly available.

Code availability The `pion` photo-ionisation code is publicly available as part of the `spex` package. The `warmabs` photo-ionisation code is publicly available as part of the `xstar` package. The `ionabs` code is publicly available for download at <https://github.com/ryotatomaru/Ionabs> as a local model for installation and use in the `xspec` package. The XSPEC model files used to make Extended Data Table 2 including the PION tables are publicly available for download at <https://zenodo.org/records/15628497>.

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Methods

Data extraction

XRISM. Data reduction was performed with the software versions of the pre-pipeline version JAXA “004_002.15Oct2023_Build7.011” and the pipeline script “03.00.011.008”, and the internal CALDB8, which corresponds to the public XRISM CALDB ver. 20240815.

The Resolve data were filtered to exclude periods affected by the Earth’s eclipse, the sunlit Earth’s limb, South Atlantic Anomaly (SAA) passages, and the initial 4300 s following the recycling of the 50-mK cooler. Events in the resulting good time intervals (GTI) were screened using pixel-to-pixel coincidence and an energy-dependent rise time cut^{54,55}. Pixels 12 (calibration pixel) and 27 (which shows unexpected gain fluctuations) were excluded. The net exposure time after filtering was 37.8 ks, with a total count rate of 72.1 s^{-1} .

A timing coefficient in the CALDB is used to set a flag for any event occurring near-in-time to another event on another pixel. The false coincidence for pixel-pixel coincidence may not be ignoreable especially in the bright sources but in our observations, the loss fraction calculated from the STATUS[4] flag is only $\sim 10\%$.

Calorimeter events are classified into “grades” based on the time interval from temporally adjacent events. Here we use only High-resolution Primary (Hp) grade, which provides the highest energy resolution. The Hp count rate was 30.1 s^{-1} , representing 42% of the total. A redistribution matrix file (RMF) was generated using `rs1mkrmf` based on the cleaned event file, with a param-

eter file of `xa_rsl_rmfparam_20190101v006.fits`. The line-spread function components considered included the Gaussian core, exponential tail to low energy, escape peaks, silicon fluorescence, and electron loss continuum (i.e., the "X" option was selected). An auxiliary response file (ARF) was generated using `xaarfgen`, assuming a point-like source at the aim point, including the additional opacity of the gate valve closed current configuration of Resolve⁵⁶.

The temperature sensitivity of the Resolve detector necessitates pixel-by-pixel correction for gain drift to maintain proper energy scale and resolution. The gain scale function is parameterized by an "effective temperature"⁵⁷, which was tracked over time for each pixel. The Mn $K\alpha$ line complex from the ⁵⁵Fe calibration source was used to calculate the effective temperature. Two gain fiducial measurements were performed at the start and end of the observation, where the entire array was illuminated by the ⁵⁵Fe source in the filter wheel. The Mn $K\alpha$ spectrum, shown in Extended Data Figure 1, has an energy resolution of 4.43 ± 0.16 eV (FWHM) and an energy offset of less than 0.16 eV. A significant temperature shift was identified after the observation, attributed to spacecraft maneuvers and orientation. In the calibration pixel, continuously illuminated by ⁵⁵Fe, the effective temperature shifted from 49.969 mK to 49.965 mK and then to 49.975 mK (Extended Data Figure 2). If the gain drift were tracked only at the fiducial points, the maximum effective temperature shift would be 0.005 mK, corresponding to a 1.5 eV energy shift (Extended Data Figure 2). To reduce this shift, we introduced an ad-hoc gain point (red circle in Extended Data Figure 2), and calculated the effective temperature difference (ΔT_{eff}) between the initial and ad-hoc gain point. Scaling from the gain change on the calibration pixel at this intermediate point, we added a new gain point for each of the other pixels (Extended Data Figure 3) and corrected

484 the X-ray energies using linear interpolation. After this observation, a gain fiducial 9 hours after a
485 maneuver was added to standard operations.

486 At high count rates, energy resolution degradation may occur due to contamination from
487 untriggered electrical cross-talk events⁵⁸. To evaluate this effect we use spectra of Cr $\text{Ly}\alpha_1$ and
488 α_2 lines from the source, which are strong and close in energy to the Mn $\text{K}\alpha$ calibration lines.
489 We compare these before and after cross-talk effect screening, but the line widths do not change
490 significantly. The results indicate that cross-talk has a negligible effect on the energy resolution
491 in this observation; therefore, we do not apply cross-talk screening in order to preserve photon
492 statistics.

493 We also check whether there is contamination of the data from pseudo-Ls (Low-resolution
494 Secondary) events. However, this is more important for fainter sources, and is negligible here
495 below 10 keV.

496 The data are not corrected for any systemic velocity offsets as these are small, with a blueshift
497 of 40 km/s for the combined effects of the velocity of the Earth round Sun and the Galactic rotation
498 at GX 13+1 position with respect to the local standard of rest. The peculiar velocity of the binary
499 system is also fairly small, at -70 ± 30 km/s¹⁰.

500 **NuSTAR.** We use the `nupipeline` from HEASOFT v.6.33.2 to reduce *NuSTAR* observation
501 30901010002. We use `nuproducts` to extract *NuSTAR* source and background spectra and to
502 create response files. The source region is a 1 arcminute circle centered on the source; we used
503 surrounding source-free regions for background.

The *NuSTAR* observation took place from 2024-02-25 12:56:09 UT to 2024-02-26 10:36:00 UT, and the *XRISM* observation occurred between 2024-02-25 02:26:51 UT and 202-02-26 00:06:46. Therefore, to maximize simultaneity and mitigate the effects of any source variability, we define the *NuSTAR* good time interval as the beginning of the *NuSTAR* observation to the end of the *XRISM* observation.

Ion-by-ion model fitting

Disc accreting neutron star continuum spectra are generally well modelled by a multicolour disc component, together with higher temperature emission from a boundary layer between the disc and NS surface. The boundary layer illuminates the disc, producing a characteristic reflection spectrum that is broadened by the relativistic velocities and strong gravity of the inner disc. We approximate this component with a broad gaussian emission line with energy fixed at 6.4 keV. The *XRISM* spectra are rebinned to require 20 counts per bin and fit between 2.1 and 18 keV using the `xspec`⁵⁹ X-ray spectral fitting package.

Relative to this absorbed disk plus blackbody and gaussssian continuum, the fit residuals show numerous narrow absorption features. We first model these features by considering each ion independently. The `kabs` model²⁸ (a local model for use in `xspec` software) calculates the full Voigt absorption line profile for a single transition in a given ion. Modelling the full series of transitions from $n = 1$ for a given ion then involves multiple `KABS` components, with ion column and velocity outflow and width tied across all the components. We develop a more convenient `xspec` local model, `Ionabs`, which packages all these together, calculating the full line series

524 from a given ion column with given kinematics in a single model component. This includes all fine
 525 structure lines, as well as the self-consistent edge structure(s) (including the L-shell edge for ions
 526 with 3 or more electrons such as FeXXIV). The Voigt profile velocity width in KABS is defined
 527 as $v_{turb}/c = (E - E_0)/\Delta E$, but the photo-ionization code `pion` (see below) uses the gaussian
 528 width $v_{rms}/c = (E - E_0)/(\sqrt{2}\Delta E)$ so here we report v_{rms} so that these can be directly compared.
 529 Transition energies, oscillator strengths, Einstein A values and the energy dependence of the cross
 530 sections are taken from Flexible Atomic Code⁶⁰. These match very well to the NIST database for
 531 H- and He-like ions.

532 It is immediately clear that most of the lines have similar kinematic structure with slow
 533 outflow velocity and very narrow velocity width. This "slow" wind component must have very
 534 high column density in order to produce the multiple higher order lines (transitions beyond $n = 8$)
 535 of Fe XXV and Fe XXVI. Such a column should have corresponding $n = 2 - 1$ $K\alpha$ transitions which
 536 are completely saturated so the lines cores should be completely black. The fact that the data never
 537 go to zero shows that there is an additional diffuse source of X-rays, most likely from the wind
 538 itself (see Figure 3). Additionally, the detailed Fe XXVI $K\alpha_1, \alpha_2$ line profile clearly shows a strong
 539 blue wing, requiring that there is an additional, faster wind component present (see Figure 3).

540 Thus we model the intrinsic spectrum absorbed by two wind components, "slow" (16 ions)
 541 and "fast" (only Fe XXV, Fe XXVI, Ni XXVII, Ni XXVIII). Modelling the diffuse emission is more
 542 challenging as it should be extremely complex, with recombination radiation from the X-ray heated
 543 material, and scattered incident continuum forming a spatially extended source which is absorbed
 544 along multiple different lines of sight through the wind. We first approximate this as electron

545 scattering alone, so a fraction f_{scatt} of the incident continuum, but a better fit to the remaining
 546 residuals around the absorption lines is if the scattered continuum is also absorbed by the "fast"
 547 wind component.

548 The model then consists of the intrinsic continuum $\text{Int} = (\text{diskbb} + \text{gauss} + \text{body})$, ab-
 549 sorbed by multiple ions grouped into two kinematic components (slow: Ionabs_s and fast: Ionabs_f),
 550 together with photoelectric absorption from neutral material (TBabs) fixed at the interstellar col-
 551 umn density of $N_{\text{H}} = 3.2 \times 10^{22} \text{ cm}^{-2}$. The model is
 552 $\text{TBabs} \times (\text{Ionabs}_s^{16} \text{Ionabs}_f^4 + f_{scatt} \text{Ionabs}_f^4) \times \text{Int}$ in XSPEC notation, where the superscripts
 553 on Ionabs show the number of ions included.

554 The resulting fit parameters are given in Extended Data Table 1. The ions in the slow com-
 555 ponent all have similar outflow velocities of $v_{out} \sim 330 \text{ km/s}$. The fast component appears to
 556 have a wider range of kinematics, with outflow velocities ranging from ~ 500 to $\sim 1000 \text{ km s}^{-1}$
 557 depending on the ion, but both fast and slow components have line widths $\sim v_{out}/2$.

558 The column densities derived for the ions in the slow component (Extended Data Table 1)
 559 are almost an order of magnitude larger than found in previous *Chandra*/HETGS data (ref.¹⁵). We
 560 estimate a lower limit to the equivalent Hydrogen column density from adding the slow component
 561 Fe XXV and Fe XXVI ion columns together, to get $N_{\text{Fe}} = 46_{-5}^{+6} \times 10^{18} \text{ cm}^{-2}$, giving $N_{\text{H}} >$
 562 $N_{\text{Fe}}/A_{\text{Fe}} = 1.4 \pm 0.2 \times 10^{24} \text{ cm}^{-2}$ for $A_{\text{Fe}} = 3.3 \times 10^{-5}$.

563 This column density is large enough that electron scattering optical depth is significant: $\tau_{es} =$
 564 $1.21 N_{\text{H}} \sigma_{\text{T}} \gtrsim 1.1$, where the factor 1.21 comes from the number of electrons per Hydrogen atom in

a fully-ionised plasma of solar abundance, and σ_T is the Thomson cross-section. The observed Fe ion columns in the slow wind component already imply that the wind is optically thick to electron scattering, and yet there should be even more material, firstly due to the fast wind and secondly since some fraction of Fe is completely stripped to Fe XXVII so produces no line signatures. This correction need not be very large for the slow wind, where the ratio of columns Fe XXVI/Fe XXV is close unity. However, this is not true for the fast wind, where the column in Fe XXVI is $2.5\times$ larger than that of Fe XXV. Thus the observed ion columns in the fast wind are likely only a small tracer of the likely column present. To correct for this requires an ionisation balance calculation.

Photoionisation modeling for ion fractions

We use the photoionised plasma model `pion` version 3.08.00, available in `SPEX`^{23,61}. We compute the ratios of different ionisation stages N^{i+1}/N^i (Extended Data Figure 4) and the ion fractions (Extended Data Figure 5) as functions of the ionisation parameter $\log \xi \equiv L/(nR^2)$. We assume an intrinsic illuminating continuum which matches the best fit incident continuum (disk blackbody plus blackbody).

All of ion ratios in the slow component are consistent with that from Fe XXVI/Fe XXV alone, giving an ionisation parameter of $\log \xi = 3.85 - 3.98$. This gives an ion fraction for completely ionised iron (Fe XXVII) of $f_{\text{xxvii}} = 0.14 - 0.23$ (Extended Data Figure 5). This increases the total iron column density in the slow wind to $N_{\text{Fe}} = 51 - 60 \times 10^{18} \text{ cm}^{-2}$, leading to an equivalent hydrogen column density $N_{\text{H}} = N_{\text{Fe}}/A_{\text{Fe}} = 1.5 - 1.8 \times 10^{24} \text{ cm}^{-2}$ and $\tau_{es} = 1.2 - 1.4$.

A similar analysis for the fast wind gives a more complex picture. The Fe ratio suggests

585 $\log \xi = 4.15 - 4.29$ (corresponding to ion fraction of Fe XXVII 0.38-0.53) giving $N_{\text{H}} \sim 4.3 -$
586 $5.6 \times 10^{22} \text{ cm}^{-2}$. However, these broader lines are less well defined in the data, and therefore more
587 sensitive to the model assumed to approximate the complex diffuse emission from the wind. Thus
588 the column density of the faster component is much more uncertain (see the full photoionisation
589 fits below).

590 The unabsorbed continuum model (without scattered flux) gives a bolometric flux of $F =$
591 $9.1 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ (13.6 eV–100 keV). Correcting this for attenuation by electron scattering
592 with $\tau_{es} = 1.2 - 1.4$ gives an intrinsic flux of $F_0 = 3.0 - 3.8 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$. The luminosity
593 of this source $L = 4\pi d^2 F_0 = 0.8 - 1 L_{\text{Edd}}$, where $d = 7 \text{ kpc}$ and $L_{\text{Edd}} = 2.1 \times 10^{38} \text{ erg s}^{-1}$.

594 The scattered fraction parameter in these fits f_{scatt} is the ratio of scattered to observed direct
595 flux. We use this to calculate the ratio of scattered to intrinsic flux $F_{\text{scatt}}/F_0 = 0.052 - 0.066$
596 and use this to estimate the solid angle of the wind, as $F_{\text{scatt}}/F_0 \approx \Omega/4\pi(1 - \exp(-\tau_{es}))$. This
597 gives $\Omega/4\pi = 0.08 \pm 0.01$, though again this is quite uncertain as it depends on the detailed wind
598 geometry and emission/absorption.

599 **Fitting with Photoionisation models**

600 We now use the same photoionised code, PION to directly fit to the data. We calculate a grid of
601 models for solar abundances, simulating absorbers with different values of column density N_{H} ,
602 ionisation parameter $\log \xi$ and turbulent velocity v_{rms} , fixing the illuminating SED shape to that
603 derived from spectral fitting. Each of the simulations has 65536 logarithmically-spaced bins to
604 cover the energy range from 10^{-4} to 10^3 keV with a resolution of 1.5 eV around 6 keV, enough to

fit *Resolve* data. In total we perform 8736 simulations with values $21 \leq \log N_{\text{H}} \leq 25$ spaced by 0.2 (21 points), $2 \leq \log \xi \leq 7$ spaced by 0.2 (26 points), and $-5 \leq \log(v_{\text{rms}}/c) \leq -2$ spaced by 0.2 (16 grid points). We fit with a single number density $n_p = 10^{14} \text{ cm}^{-3}$ to reduce the size of the tables (see Main text and below); we calculate the population levels from radiative recombination, cascade, radiative and collisional excitation correctly for meta-stable levels^{42,62}. We build these results into a multiplicative absorption table model⁴⁶ for use in XSPEC.

Diffuse continuum approximated by absorbed scattered flux We replace the multiple ion-by-ion absorption components with two `pion` absorption components (one fast: `absf` and one slow: `abss`). As above, we assume that the diffuse emission has the same shape as the incident continuum and that this scattered component is absorbed by the fast wind. We represent this model in XSPEC form as $\text{TBabs} \times (\text{abs}_s \text{abs}_f \text{Int} + f_{\text{scatt}} \text{abs}_f \text{Int})$.

Remarkably, the goodness of the fit is not far from that of the “ion-by-ion” fit, which allowed free element abundances and allowed every ion to have different kinematics and ion ratios ($\chi^2 = 14726/13555$ i.e. 52 fewer free parameters, for $\Delta\chi^2 \sim 550$). This gives very similar plasma parameters for the slow component as derived from the ion-by-ion fitting, namely $\log \xi = 3.93^{+0.01}_{-0.02}$ and $N_{\text{H}} = 154^{+8}_{-6} \times 10^{22} \text{ cm}^{-2}$. However, the fast component now has a higher ionisation parameter ($\log \xi = 4.49$) and hence a higher equivalent column density of $N_{\text{H}} = 9^{+2}_{-1} \times 10^{22} \text{ cm}^{-2}$. This shows that the fast component parameters are more sensitive to the details of the model, but that the slow component is very robust, and robustly gives an optical depth $\tau_{es} > 1$.

Diffuse component including line/recombination emission. A better approximation to the dif-

fuse/scattered continuum requires using `pion` to calculate the emitted line/recombination continuum from the photoionised material in addition to the absorption lines. We take the same incident spectrum and density as for the absorption table model to generate an additive table model for XSPEC (hereafter `emm`), but this time we set the solid angle fraction $\Omega/4\pi = 1.0$. In principle, the resulting emission normalisations allow the solid angle to be independently estimated, but these will be dependent on details of the radiation transfer through the optically thick wind, so we do not use them here.

We tie the ionisation parameter and column density to be the same for the absorbing and emitting plasma. We expect the emission should arise from all azimuths, so we fix the outflow velocity to zero, and allow the broadening to be free. We allow this to be somewhat self absorbed by the wind in our line of sight, but caution that this is just an approximation to a more complex geometry that requires a full radiation transfer calculation.

The final model is $\text{TBabs} \times (\text{abs}_s \text{abs}_f \text{Int} + \text{f}_{\text{scatt}} \text{abs}_f \text{Int} + \text{abs}_s \text{emm}_f + \text{f}_{\text{scatt}} \text{emm}_f + \text{emm}_s)$, where again we fix `tbabs` to the interstellar column density of $N_{\text{H}} = 3.2 \times 10^{22} \text{ cm}^{-2}$. This gives our best description of the spectrum (Extended Data Table 2), and is the model shown in Figure 1. This gives a goodness of fit of 14339/13551. This has 4 more free parameters than the previous description of the diffuse flux, but gives $\Delta\chi^2 = -386$. It is now statistically equivalent to the ion-by-ion fits in Extended Data Table 1, as it has 48 fewer free parameters for an increase of $\Delta\chi^2 = +151$.

The emission lines are not obvious by eye as in this model they are dominated by the fast

component and are therefore moderately broadened. Nonetheless, the resultant P Cygni profile can be seen in FeXXVI Ly $\alpha_{1,2}$ at around 6.94 keV as shown in Figure 3. The emission lines also contribute to the shape of the saturated line cores, and this more complex model shifts the ionisation parameter of the fast wind to even higher values, $\log \xi = 4.69^{+0.03}_{-0.04}$ requiring even higher column densities: $N_{\text{H}} = 80 \times 10^{22} \text{ cm}^{-2}$. Again, the parameters of the slow wind are mostly consistent with previous models, with just slightly lower column ($N_{\text{H}} = 132^{+7}_{-8} \times 10^{22} \text{ cm}^{-2}$) and ionisation state ($\log \xi = 3.88 \pm 0.01$), but similar kinematics, and scattered fraction.

We also perform fits with the XSTAR model `warmabs`⁶³ to explore the overall robustness of our photoionisation analysis. For `warmabs`, we calculate electron level populations using the best fit continuum from fits to a model consisting of an absorbed disc plus `nthcomp`^{64,65} with Gaussian lines and a smeared edge near 8 keV. Fits to the Resolve spectrum with `warmabs` were qualitatively and quantitatively very similar to the `pion` fits, requiring a high-column component with a smaller turbulent line width and blueshift and a more highly-ionised, broader, and faster component. These fits will be presented in detail elsewhere, but we note that despite different assumptions about the ionising continuum, radiative transfer, absorption/emission geometry, and the different codes, we still find a total equivalent of the slow wind column density in excess of $1.4 \times 10^{24} \text{ cm}^{-2}$.

Wind Geometry

We assume that the wind is a continuous structure so the outer edge of the fast wind must coincide with the inner edge of the slow wind³². In other words, the column density of the fast and slow

winds must be given by

$$N_{\text{H,f}} = \int_{R_{\text{f}}}^{R_{\text{s}}} n(R) dR, \quad N_{\text{H,s}} = \int_{R_{\text{s}}}^{R_{\text{out}}} n(R) dR,$$

where $R_{\text{s}} = R_{\text{f}} + \Delta R_{\text{f}}$, ΔR_{f} is the width of the fast wind, and $n(r)$ is the density profile of the wind. But the relative locations of the fast and slow winds are also set by their relative ionisation parameters. If the ionisation parameter at the inner edge of the fast wind is $\xi_{\text{f}} = L_0/n_{\text{f}}R_{\text{f}}^2$, then the ionisation parameter at the inner edge of the slow wind must be $\xi_{\text{s}} = L_0 \exp(-\tau_{\text{f}})/n_{\text{s}}R_{\text{s}}^2$. Here n_{f} and n_{s} are the densities of the wind at R_{f} and R_{s} , respectively, while R_{out} is the outermost radius at which the wind is produced (which need not be the same as the disc outer radius). The factor $\exp(-\tau_{\text{f}})$ is an approximation of the attenuation of the radiation field by the fast wind. This is appropriate for a relatively small solid angle wind, as inferred here.

For a self-consistent solution, the radius of the slow wind as inferred from the column density of the fast wind must match the radius implied by the relative ionisation of the two zones. This gives 4 independent constraints, so we can solve for (at most) 4 independent parameters. We first assume a constant density wind, which gives $n_{\text{f}} = n_{\text{s}} = 1.6 \times 10^{14} \text{ cm}^{-3}$, for $R_{\text{f}} = 4.7 \times 10^9 \text{ cm}$, $R_{\text{s}} = 1.0 \times 10^{10} \text{ cm}$, and $R_{\text{out}} = 1.8 \times 10^{10} \text{ cm}$. Alternatively, we assume a power law density distribution $n = n_{\text{f}}(R/R_{\text{f}})^{-x}$ for $R_{\text{f}} < R < R_{\text{out}} = 10^{12} \text{ cm}$ which is the outer disc radius. This has $n_{\text{f}} = 0.9 \times 10^{14} \text{ cm}^{-3}$ with $x = 1.1$ for $R_{\text{f}} = 6.3 \times 10^9 \text{ cm}$, $R_{\text{s}} = 3.7 \times 10^{10} \text{ cm}$ (giving $n_{\text{s}} = n(R_{\text{s}}) = 1.3 \times 10^{13} \text{ cm}^{-3}$).

These densities are very high but the predominantly H- and He-like ions seen have no density diagnostic potential. Instead, previous work on the black hole binary GRO J1655-40, which

also showed evidence for a Compton thick wind from a likely super-Eddington state^{30,42,66,67}, measured density directly from a meta-stable L-shell absorption line of B-like Fe XXII^{42,68,69}. This line transition at ~ 1 keV is outside of the current Resolve bandpass, and would likely not be present in the higher ionisation state seen in the GX 13+1 outflow. However, weak meta-stable lines from K-shell Be-like Fe XXIII around 6.6 keV may be used to probe the density⁶² in future modeling.

In principle, a thermal wind may be launched from all radii $R \gtrsim 0.2R_{\text{IC}}$, where R_{IC} is the Compton radius³⁷. For GX 13+1, this nominal limit is approximately 3.3×10^{10} cm, a factor of a few larger than the inferred launch radius of the fast wind. However, thermal-radiative winds can be expected from much smaller radii when the luminosity approaches the Eddington limit³⁵, so our radii are likely consistent with a thermal-radiative wind.

Finally, we calculate the mass loss rate in the wind. Here the wind is being launched from all radii on the disc from $R_{\text{f}} - R_{\text{out}}$, so we cannot use the standard mass continuity expressions as the wind mass is increasing over this range. Instead, we calculate the total wind mass in this region, M , and the time, t , it takes to expand out of this region as

$$M = \int_{R_{\text{f}}}^{R_{\text{out}}} 4\pi R^2 (\Omega/4\pi) n(R) m dR, \quad t = \int_{R_{\text{f}}}^{R_{\text{out}}} \frac{dR}{v(R)} = \frac{R_{\text{s}} - R_{\text{f}}}{v_{\text{f}}} + \frac{R_{\text{out}} - R_{\text{s}}}{v_{\text{s}}}$$

where $m = 2.4 \times 10^{-24}$ g is the average atomic mass per Hydrogen atom in a cosmic gas, Ω is the solid angle of the wind and $v(R)$ is the radial velocity profile.

For the constant density wind, these give $\dot{M} = M/t = 2.4 - 6.6 \times 10^{18}$ g/s for the solid angles discussed in the Main text ($0.08 \leq \Omega/4\pi \leq 0.22$). This is very similar to the estimates given by mass continuity $\dot{M} = 4\pi R^2 n(R) v(R) m (\Omega/4\pi)$ which can be rewritten for the fast

696 wind as $\dot{M}_f = 4\pi m(\Omega/4\pi)(L/\xi_f) = 0.5 - 1.5 \times 10^{18}$ g/s while the slow wind gives $\dot{M}_f =$
697 $4\pi m(\Omega/4\pi)L \exp(-\tau_f)/\xi_s = 1.3 - 3.7 \times 10^{18}$ g/s. However, the power law density profile with
698 $x = 1.1$ has much more mass at larger radii, so gives much larger $\dot{M} = M/t = 14 - 39 \times 10^{18}$ g/s.

699 Even the lowest estimates for the mass loss rate from constant density assumptions are com-
700 parable with the central mass accretion rate of 3.9×10^{18} g/s required to power the inferred X-ray
701 luminosity, while the largest estimates have up to $10\times$ more matter ejected than is accreted.

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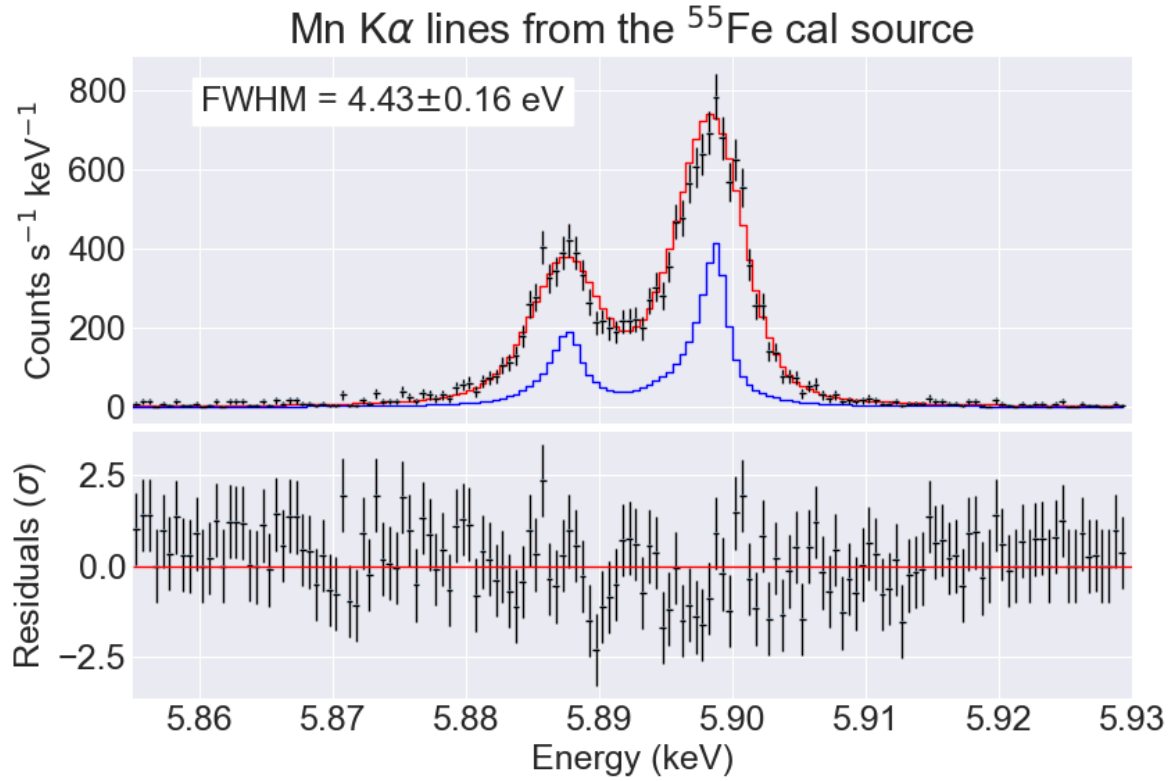
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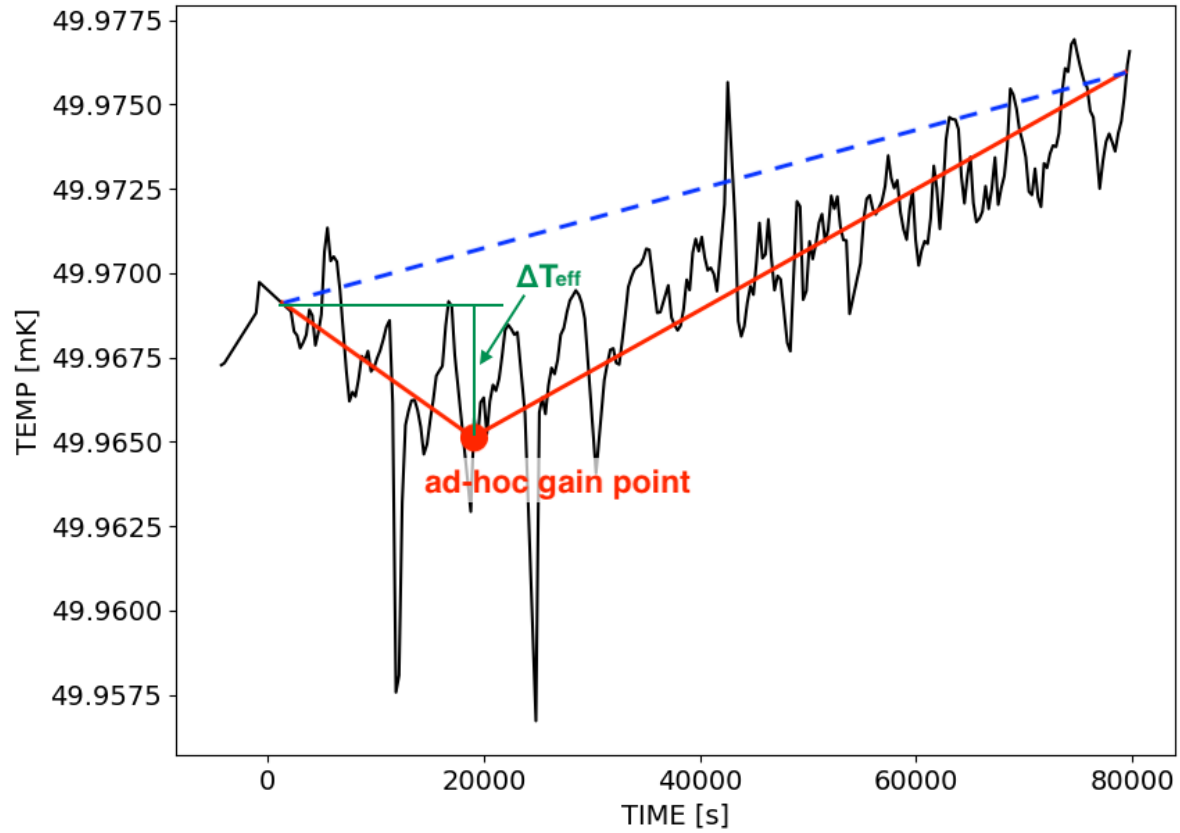
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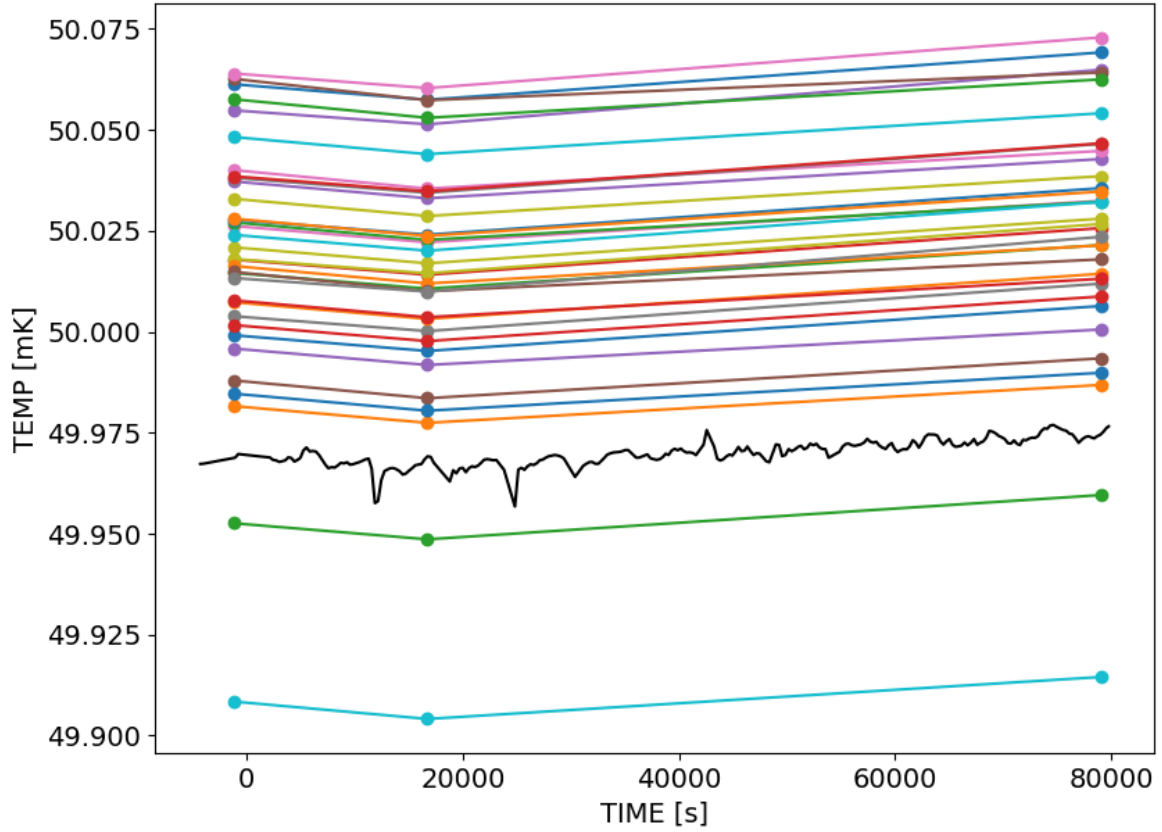
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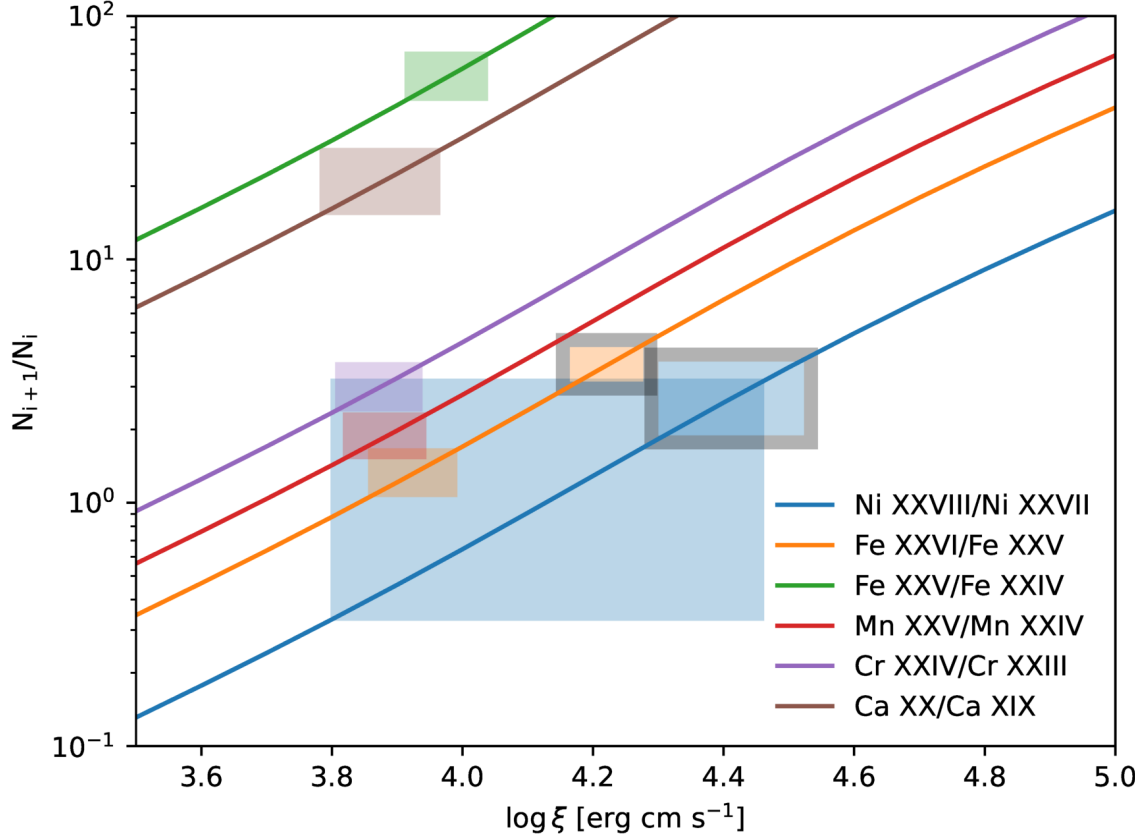
Extended Data Fig. 1: Mn $K\alpha$ lines from the ^{55}Fe source in the filter wheel. The black bins show the Hp spectrum extracted using two gain fiducial points, summing the 34 pixels. The blue line shows the intrinsic line profile, whereas the red one represents the best fit model, with additional Gaussian broadening of FWHM=4.43 eV. The lower panel shows the residuals between the data and the model, indicating that this is a good description.



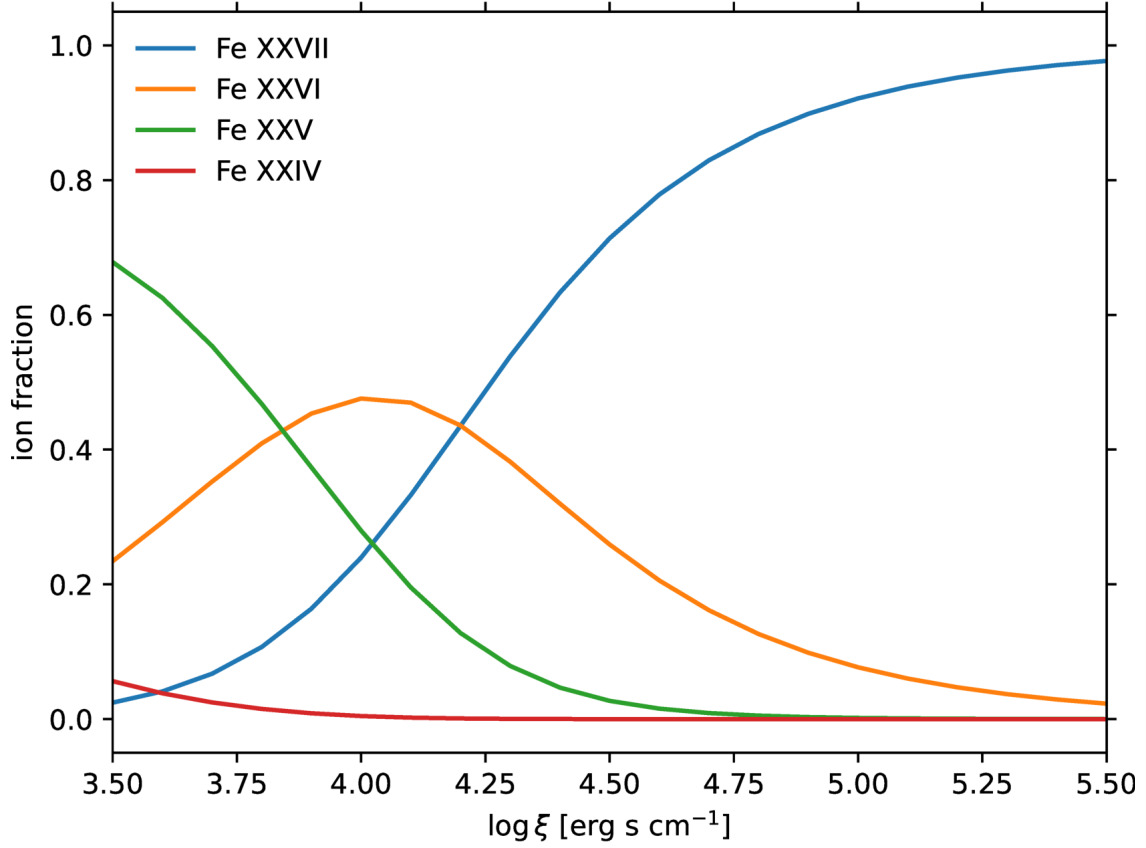
Extended Data Fig. 2: Effective temperature of the calibration pixel versus time. The effective temperature across the observation is shown as a solid black line, compared to a linear interpolation between the measurements at the start and end of the observation (blue dashed line). We introduce an ad-hoc gain point (red filled circle, with a temperature ΔT_{eff} below the first gain point), to give a better match (red solid line).



Extended Data Fig. 3: Effective temperature variations in all pixels except 27. Each pixel has an effective temperature estimate corresponding to the gain fiducial measurements at the beginning and end of the observation. We introduced an additional gain point by scaling the ad-hoc gain point from the calibration pixel (see Extended Data Fig. 2) to each individual pixel (see the middle point in each colored line). The black line shows the calibration pixel, which is tracked continuously, for reference.



Extended Data Fig. 4: Ion ratio as a function of ionisation parameter. We computed the ground state populations for each ion using the `pion` code as in Methods. The ratio of these populations (equivalently, the ratio of the column densities in different ions) is sensitive to the ionisation parameter, as shown. Using the ratio of column densities taken from Extended Data Table 1, we estimate the ionisation parameter of the slow component in our ion-by-ion fits as $\log \xi \sim 3.9$ (shaded regions), and the fast component of Fe and Ni as $\log \xi = 4.15 - 4.53$ (shaded regions with black frames).



Extended Data Fig. 5: Ion fractions of Fe versus the ionisation parameter. This is computed using `pion` as described in Methods, assuming that the gas is photoionised by the continuum shape observed. We estimate the ionisation parameter from our ion-by-ion fits using Extended Data Figure 4, then used the curves above to determine the column density of completely-ionised Iron (Fe XXVII).

Extended Data Table 1: Fit with ion-by-ion absorption plus scattered flux.

^a $N_{\text{ion},18}$ is the ion column density in units of 10^{18} cm^{-2} .

^b Model is $\text{TBabs} \times (\text{Ionabs}_{\text{s}}^{16} \text{Ionabs}_{\text{f}}^4 + f_{\text{scatt}} \text{Ionabs}_{\text{f}}^4) \times \text{Int}$

^f indicates fixed parameters. All other parameter errors are calculated at 90% confidence levels.

Extended Data Table 2: Fit with two `pion` absorbers plus their emission and scattered flux.

^a The column density and ionisation state are tied between the absorption and emission.

^b model is $\text{TBabs} \times (\text{abs}_s \text{abs}_f \text{Int} + f_{\text{scatt}} \text{abs}_f \text{Int} + \text{abs}_s \text{emm}_f + f_{\text{scatt}} \text{emm}_f + \text{emm}_s)$

^f indicates fixed parameters. All other parameter errors are calculated at 90% confidence levels.