A mass of less than 15 solar masses for the black hole in an ultraluminous X-ray source

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Most ultraluminous X-ray sources1 have a typical set of properties not seen in Galactic stellar-mass black holes. They have luminosities of more than $3 \times 10^{39} \text{ergs s}^{-1}$ and unusual soft X-ray components (with a typical temperature of less than about 0.3 kiloelectronvolts) and a characteristic downturn2,3 in their spectra above about 5 kiloelectronvolts. Navigating such properties have been interpreted either as evidence of intermediate-mass black holes4 or as emission from stellar-mass black holes accreting above their Eddington limit5, analogous to some Galactic black holes at peak luminosity6,7. Recently, a very soft X-ray spectrum was observed in a rare and transient stellar-mass black hole8. Here we report that the X-ray source P13 in the galaxy NGC 77939 is in a binary system with a period of about 64 days and exhibits all three canonical properties of ultraluminous sources. By modeling the strong optical and ultraviolet modulations arising from X-ray heating of the B9a donor star, we constrain the black hole mass to be less than 15 solar masses. Our results demonstrate that in P13, soft thermal emission and spectral curvature are indeed signatures of supercritical accretion. By analogy, ultraluminous X-ray sources with similar X-ray spectra and luminosities of up to a few times $10^{39} \text{ergs per second}$ can be explained by supercritical accretion onto massive stellar-mass black holes.

We organized an X-ray–ultraviolet–optical spectrophotometric monitoring programme of the ultraluminous X-ray source (ULX) P1310 from late 2009 until late 2013 using NASA’s Swift and Chandra satellites, the European Space Agency’s XMM-Newton satellite and the European Southern Observatory’s Very Large Telescope (VLT). These data were supplemented by photometry obtained at the Warsaw 1.3 m telescope (Las Campanas Observatory) in 2004 and 2005 and by an archival Chandra observation obtained in 2003. Details of the observations and data reduction as well as further analysis of the results are reported in the Supplementary Information.

Chandra detected P13 in 200311 with a 0.3–10 keV X-ray luminosity of $L_X(0.3–10 \text{keV}) \approx 4 \times 10^{39} \text{erg s}^{-1}$. Our 73 d-long Swift X-ray Telescope (XRT) monitoring carried out in 2010 recorded a 0.3–10 keV X-ray luminosity in the range of $(4.8 \pm 0.5) \times 10^{39} \text{erg s}^{-1}$ down to less than $1.6 \times 10^{38} \text{erg s}^{-1}$ on one occasion. A similar X-ray luminosity, of $(2.0 \pm 0.1) \times 10^{39} \text{erg s}^{-1}$, was detected in our last XMM-Newton observation in November 2013. The 2003 Chandra spectrum displays a spectral break at $\approx 4.2$ keV. Our 2013 XMM-Newton observation confirms the break seen by Chandra and reveals a soft disk-black-body-like component with $k_BT_\text{in} = 0.3 \text{keV}$, where $k_B$ is Boltzmann’s constant and $T_\text{in}$ is the temperature at the inner disk radius (Extended Data Table 1 and Extended Data Fig. 1). Therefore, P13 exhibits all the hallmarks of a canonical ultraluminous X-ray state2. Remarkably, Swift/XRT did not detect P13 in any of the individual pointings performed from August 2011 until June 2013. Stacking Swift faint-state data reveals the source at $L_X(0.3–10 \text{keV}) = (5 \pm 1) \times 10^{37} \text{erg s}^{-1}$ (90% confidence level), which is a factor of 10 less than in the previously seen bright X-ray state. Scheduled and serendipitous Chandra and XMM-Newton observations carried out in 2011 and 2012 detected the source at the same low X-ray luminosity and will be reported elsewhere.

Optical spectra suggest a B9I spectral type (Fig. 1). In addition to high-order Balmer absorption lines, the spectrum exhibits Balmer emission up to at least Hγ as well as He i $\lambda 4,686$ (that is, at a wavelength of $\lambda = 4,686 \text{Å}$) and Bowen C iii–N ii emission. Assuming that minimum light (visual magnitude, $V = 20.50$ mag; Extended Data Figs 2a–d and 3a) represents stellar light yields an absolute magnitude of only $M_V = -7.50$ mag (distance, $d = 3.7$ Mpc (ref. 14); mean extinction, $A_V = 0.16$ mag (refs 15, 16)). Such a high optical luminosity implies a type Ia supernova classification with an initial mass of 20–25 solar masses ($M_{\odot}$) and a present mass of $18M_{\odot} – 23M_{\odot}$ (ref. 17). Because the bolometric luminosity is $L_{\text{bol}} \approx 5 \times 10^{39} \text{erg} \text{s}^{-1}$, which is almost one-tenth of the maximum observed X-ray luminosity, we expect X-ray heating effects to be noticeable.

The data obtained by Swift/UVOT and the Swift Ultraviolet and Optical Telescope (UVOT) u-band and V-band 2010 monitorings all show two consecutive maxima, providing possible hints of a $\sim 2$ month-long orbital period. The power spectrum analysis of the 2004–2011 V-band light curve (Extended Data Fig. 4) reveals two aliasing periods, one at $P = 65.165$ d and one at $P = 63.340$ d. Corresponding periodicities are found in the He i radial velocities. Importantly, analysing times of visual and ultraviolet photometric maxima over a 8 yr time interval reveals a phase jitter of up to $\pm 0.09$, which might reflect a superorbital period of $\sim 5–8.8$ yr (Extended Data Figs 5 and 6).

The pattern of radial velocity variations with orbital phase changed very significantly between 2010 (X-ray bright state) and 2011 (X-ray faint state) (Extended Data Fig. 7). Balmer absorption lines show what may be a coherent variation with orbital phase in 2010, and the pattern of variability is clearly more complex in 2011. The total velocity amplitude of the absorption lines is $\sim 160 \text{km s}^{-1}$. Interestingly, the shape and amplitude of the optical light curve (Extended Data Fig. 8) and the mean value of the He i $\lambda 4,686$ equivalent width do not seem to depend on the observed X-ray luminosity. The relative amplitude of the $u$-band (central wavelength, $\lambda_{\text{central}} = 3,465 \text{Å}$; light-curve full amplitude, $\Delta u = 1.0 \text{mag}$) and V-band ($\lambda_{\text{central}} = 5,500 \text{Å}$; $\Delta V = 0.5 \text{mag}$) light curves and the behaviour of the $V-I$ colour index suggest that the hemisphere of the supergiant star facing the compact companion experiences a strong X-ray heating effect. An X-ray source with a tenth of the nominal X-ray luminosity would brighten the star by only $\sim 0.1 \text{mag}$ in $V$ at maximum light and would have basically no effect in the faint X-ray state. Therefore, we conclude that in 2011 part of the companion star photosphere continued to be illuminated by a luminous X-ray source that is shielded from our view. The Galactic X-ray binary Hercules X-1 exhibits similar bright and faint X-ray states18, as well as periodic phase shifts of photometric maxima19. By analogy, we suggest that a tilted, precessing accretion disk is at the origin both of the bright and faint X-ray states and of the phase jitter of optical maximum light.
To constrain the geometry and dynamics of the system, we simultaneously fitted the V-band and UVOT u-band light curves using the eclipsing light curve (ELC) code. We tested four X-ray luminosity levels, namely 0.7, 1, 1.4 and 2 times a nominal value of $4.2 \times 10^{39}$ erg s$^{-1}$ (derived from the diskbb + comptt fit to the Chandra spectrum extrapolated to the 0.3–20 keV range), to account for the observed X-ray variability and for a possible undetected component radiating at energies below or above the observed 0.3–10 keV X-ray range. The ELC model included a dark accretion disk casting X-ray shadows on the X-ray-heated stellar hemisphere. Modelling the optical disk emission caused by X-ray heating, and the absence of veiling in the high-order Balmer absorption lines, indicates that optical light is fully dominated by stellar emission (Extended Data Fig. 9). Examples of fitted light curves are shown in Fig. 2.

We explored the parameter space spanning black-hole/star mass ratios $M_{\text{BH}}/M_{\star}$ = 0.1–10; inclinations from 0$^\circ$ to 90$^\circ$; effective stellar temperatures $T_{\text{eff}}$ = 10,000, 11,000 and 12,000 K; the four choices of $L_X$ mentioned above; B9Ia star masses of 18$M_{\odot}$ and 23$M_{\odot}$; and two rotation states of the mass-donor star, namely periastron-synchronized and non-rotating. In each case, the B9Ia star was assumed to fill its Roche lobe at periastron because the total wind mass loss rate of a B9Ia star is lower or equal to the mass accretion rate required to explain the bright X-ray state ($\sim 7 \times 10^{-7}M_{\odot}$ yr$^{-1}$). The accretion disk had a fixed radius of 0.7 times the Roche lobe radius at periastron. For each of these parameters, we obtained best-fit values for the remaining orbital and disk parameters. We computed the bolometric magnitude $M_{\text{bol}}$ by equating the radius of the mass-donor star with that of the corresponding volume-averaged Roche lobe at periastron. We then constrained the range of possible masses of the X-ray source by forcing ELC fits to be acceptable at the 99.7% level, forcing computed bolometric magnitudes to be consistent with observations and forcing possible eclipses to be shorter than the maximum of 7 d allowed by Swift 2010 data. All acceptable orbital solutions implied velocity amplitudes of Balmer absorption lines smaller than the maximum observed range.

All constraints converge towards a black hole mass less than $\sim 15M_{\odot}$, irrespective of the incident X-ray luminosity in the range considered here (Fig. 3). Black holes more massive than $\sim 15M_{\odot}$ imply Roche lobes that are too small at periastron to accommodate the large B9Ia star. All acceptable orbital solutions require a significant eccentricity of $e = 0.27$–0.41 (Table 1). The full radial velocity amplitude of the compact object varies from 120 to 290 km s$^{-1}$, a range of values consistent with those observed in 2010 and 2011 for the He ii emission line.

The evolved nature of the donor star suggests that mass transfer to the black hole happens on a thermal timescale ($\sim 10^9$ yr) as the supergiant...
Figure 2 | Examples of V and u light-curve fits. Examples of acceptable models, using the ELC code, obtained by simultaneously fitting V and Swift/UVOT u light curves. Model parameters: mass-donor mass, 23$M_\odot$; $T_{\text{eff}} = 12,000$ K; $M_{\text{BH}} = 6.9M_\odot$; log($L_\text{X}$) = 39.925; $i = 80^\circ$; $e = 0.33$; periastron angle, 93°. The disk radius has a $\beta$ opening angle of 6.9°. $\chi^2 = 38.19$ for 39 degrees of freedom. Error bars in all panels show statistical uncertainties at the 1σ level. We assume an orbital period of 63.52 d and a superorbital period of 2,620 d. The spin angular velocity of the donor star is synchronized with its orbital angular velocity at periastron. a, b, ELC model fits to the u (a) and binned V (b) light curves. Occultation of the X-ray-heated star hemisphere by the dark disk accounts for the small dip present at maximum light. c, Model radial velocity curve of the X-ray source overplotted on observed He II emission line radial velocities. The model curve appears shifted by −0.3 in phase with respect to the observations. This suggests that in P13 the location of the He II λ4,686 emitting region does not accurately trace the motion of the compact object, a situation similar to that encountered in several Galactic low-mass X-ray binaries

Figure 3 | Constraints on the mass of the compact star. Constraints on the mass of the compact object plotted for $T_{\text{eff}} = 11,000 \pm 1,000$ K (consistent with the B9 Ia spectral type of the mass-donor star); log($L_\text{X}$) = 39.475, 39.625, 39.775 and 39.925; B9 Ia stellar masses of 18$M_\odot$ and 23$M_\odot$, mass ratios $M_{\text{BH}}/M_*$ in the range 0.1–10, and mass-donor stars non rotating (a) or synchronized with orbital rotation at periastron (b). For each mass-donor star mass, system inclination, mass ratio and $T_{\text{eff}}$, the best ELC fit to the u and V light curves provides the eccentricity, the periastron angle and phase, and the radial velocity of the light barycentre of the companion star and of the X-ray source. We show only solutions with $M_{\text{BH}} > 3M_\odot$. Small black-filled squares: solutions providing statistically acceptable fits to the light-curves at the 99.7% confidence level. Large symbols: Solutions implying mass-donor optical luminosities compatible with the size of the Roche lobe radius at periastron. Large green-filled squares: excluded solutions implying eclipse durations longer than the maximum allowed by our Swift X-ray monitoring in 2010. Large red diamonds: finally allowed black hole masses considering all possible values of the input parameters. The maximum allowed black hole masses are $\sim 7M_\odot$ and $\sim 15M_\odot$ for a synchronized mass-donor star and a non-rotating mass-donor star, respectively. These values are obtained for $M_* = 23M_\odot$. 

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Table 1 | Allowed range of orbital parameters

| Parameter       | Yes               | No               |
|-----------------|-------------------|------------------|
| $M_{\text{BH}}$ (M$_\odot$) | 3.45–6.9          | 3.45–14.95       |
| $e$             | 0.77              | 0.73             |
| $\omega$ (°)    | 79–118            | 84–124           |
| $\phi$ (°)      | 25–80             | 20–80            |
| $M_{\text{in}}$ (mag) | −7.72 to −7.03    | −7.89 to −6.97   |
| $R_{\text{Roche}}$ (R$_\odot$) | 64–77             | 64–82            |
| $X$-ray heating (mag) | 0–0.04           | 0–0.09           |
| $RV_1$ (km s$^{-1}$) | 171–285           | 124–286          |
| $RV_2$ (km s$^{-1}$) | 18–64             | 19–116           |

$M_{\text{BH}}$ is the minimum reduced value (39 degrees of freedom) of all acceptable solutions; $e$ is the periastron angle; $R_{\text{Roche}}$ is the radius of the Roche lobe of the mass donor star in solar radii; $\omega$ is the angle between the orbital plane and the line of sight; $\phi$ is the phase in the orbital cycle; $M_{\text{in}}$ and $R_{\text{Roche}}$ are the full amplitudes of the radial velocity of the mass-donor star and of the black hole, respectively.

rapidly expands. This is more than an order of magnitude shorter than its main-sequence lifetime, and implies that supergiant ULXs are much rarer than systems with unevolved mass donors. Given the significant eccentricity of the orbit, it is likely that Roche lobe overflow started only after the star began crossing the Hertzsprung gap.

The intrinsic X-ray luminosity of $\sim 4 \times 10^{39}$ erg s$^{-1}$ is about twice the Eddington luminosity of a 15 M$_\odot$ accreting black hole. We thus confirm that P13 is a genuine Eddington or super-Eddington source and that its extreme X-ray luminosity does not reflect the presence of an intermediate-mass black hole. Hence, we do have direct evidence that the characteristic ULX X-ray spectrum, with both a medium energy break and a soft X-ray excess, is the signature of an Eddington or super-Eddington regime.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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Author Contributions C.M. wrote the manuscript with comments from all authors. M.W.P. identified the optical counterpart of P13 and initiated optical observations at the ESO. C.M. and F.G. analysed the spectroscopic and photometric data from several runs at the ESO Very Large Telescope. F.G. analysed the HST data. G.P. provided photometric data from the Warsaw telescope at the Las Campanas Observatory. R.S., M.W.P. and C.M. designed and analysed the Chandra, XMM-Newton and Swift X-ray observations. C.M. carried out the light-curve fitting using the ELI code. C.M., M.W.P., R.S. and F.G. made significant contributions to the interpretation and discussion of the data. All authors participated in the review of the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to C.M. (christian.motch@unistra.fr).

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Extended Data Figure 1 | XMM-Newton and Chandra bright-state spectra. The $E \times f(E)$ unfolded energy distribution of the 2003 Chandra/ACIS-S (upper (red) data points) and of the 2013 XMM-Newton/EPIC combined spectra (lower (blue) data points) fitted with the diskir model. Best-fit model parameters are listed in Extended Data Table 1. Spectra shown here have been re-binned with a minimum signal-to-noise ratio of 8 in each bin for display purposes. Error bars show the 1σ statistical error.
Extended Data Figure 2 | Optical data. Optical light and radial velocity curves of P13. a, b, 2004 and 2005 Las Campanas photometry; c, d, ESO VLT light curves; e, f, equivalent width of the HeII λ4,686 emission line; g–j, radial velocity curves of Balmer absorption lines (g, h) and the HeII emission line (i, j). P13 was X-ray bright in 2010 (c, e, g, i) and X-ray faint in 2011 (d, f, h, j). Red arrows in d mark times of the Chandra (near optical maximum) and Swift observations which detected P13 in the faint-X-ray state. Error bars in all panels show statistical uncertainties at the 1σ level. MJD, modified Julian date.
Extended Data Figure 3 | The 2010 observations. a, Red squares, UVOT u band ($\lambda_{\text{eff}} = 3,470$ Å); black lozenges, ESO VLT V light curve. Note the successive maxima separated by $\sim 64$ d, more pronounced in the u band ($\Delta u < 1.0$ mag) than in V ($\Delta V < 0.5$ mag). b, Swift/XRT 0.3–10 keV light curve obtained from 2010 August 16 to 2010 October 27. The count-to-flux factor was computed by fitting the XMM-Newton diskir model to the average bright-state spectrum. This implies unabsorbed (0.3–10 keV) X-ray luminosities in the range of $4.8 \times 10^{39}$ erg s$^{-1}$ down to less than $1.6 \times 10^{38}$ erg s$^{-1}$ on MJD 55492.9 with a weighted average of $(2.8 \pm 0.2) \times 10^{39}$ erg s$^{-1}$. Error bars in all panels show statistical uncertainties at the 1σ level. Errors in V (not shown) are typically lower than 0.04 mag.
Extended Data Figure 4 | Power spectra. a, Lomb–Scargle power spectrum of the entire V light curve. b, Lomb–Scargle power spectrum of the He II radial velocity curve. The dotted line shows the position of the highest peak of the V-band periodogram ($P = 65.165 \text{ d}$).
Extended Data Figure 5 | UVOT multiband photometric light curve. Times of photometric maxima used to constrain the superorbital period in 2012 and 2013 are shown with arrows. Black squares, $u$ ($\lambda_{\text{central}} = 3.465$ Å); green lozenges, $uw1$ ($\lambda_{\text{central}} = 2.600$ Å); red lozenges, $um2$ ($\lambda_{\text{central}} = 2.246$ Å); blue lozenges, $uw2$ ($\lambda_{\text{central}} = 1.928$ Å). Error bars show statistical uncertainties at the 1σ level.
Extended Data Figure 6 | Orbital and superorbital periods. Best-fit orbital ($P_{\text{orb}} = 63.52$ d) and superorbital ($P_s = 2.620$ d $\approx 7.2$ yr) solutions accounting for the periodic phase jitter of times of optical/ultraviolet photometric maxima. Error bars show 1$\sigma$ statistical errors. Five times at which maximum light occurred were extracted from the V-band photometry at MJD 53314.8 $\pm$ 3, 53636.4 $\pm$ 3, 53699.4 $\pm$ 2 (Las Campanas) and MJD 55532.8 $\pm$ 3, 55788.0 $\pm$ 2 (ESO VLT) and four from the UVOT photometry at MJD 55468.0 $\pm$ 2 (u), 56175.0 $\pm$ 3 (u), 56243.0 $\pm$ 2 (u, um2, uw2), 56303.0 $\pm$ 2 (u, um2, uw2).
Extended Data Figure 7 | Folded radial velocity curves. He II λ4,686 (a) and Balmer absorption (b) radial velocity curves folded with the best-fit combination of orbital and superorbital periods ($P_{\text{orb}} = 63.52$ d and $P_s = 2,620$ d). Phase 0 corresponds to maximum light. Blue, ESO 2009; black, ESO 2010; red, ESO 2011. The He II line displays a clear velocity change with orbital phase. Error bars in all panels show statistical uncertainties at the 1σ level.
Extended Data Figure 8 | Folded light curves. $u$, $V$ and $V-I$ light curves folded with the best-fit combination of orbital and superorbital periods ($P_{\text{orb}} = 63.52$ d and $P_s = 2,620$ d). Phase 0 corresponds to the predicted time of maximum optical light. Note the different scales used to plot the $u$ and $V$ light curves. a, $u$: black, 2010 X-ray bright-state run; red, data acquired during the faint-X-ray state in the time interval 2012 September 2 to 2013 January 12. b, $V$: black, Las Campanas; red, ESO 2010 (X-ray bright); blue, ESO 2011 (X-ray faint). c, Binned $V-I$ light curve. The $V-I$ index is plotted on an arbitrary scale. Error bars in all panels show statistical uncertainties at the 1σ level.
Extended Data Figure 9 | High-order Balmer lines. Normalized mean P13 spectrum away from maximum light (V ≈ 20.3 mag, shifted up by 0.25 for clarity) compared to that of the B8Ia star β Orionis (shifted down by 0.2). The equivalent widths of the high-order Balmer lines H8 and H9 are almost identical in the two stars. The higher interstellar absorption towards P13 than towards Orion is responsible for the stronger Ca II line in the ULX spectrum. Residual Balmer emission already adds to the photospheric Hδ absorption line and the He line is blended with the Ca II interstellar line. The mean equivalent width of the H8 and H9 Balmer lines are 1.52 ± 0.09 and 1.56 ± 0.08 for β Ori and P13, respectively (1σ errors), consistent with no line veiling in P13.
### Extended Data Table 1 | X-ray spectral fits

| Parameter | Value in C03 | Value in X13 |
|-----------|---------------|---------------|
| $n_{H,\text{int}} \times 10^{20}$ cm$^{-2}$ | [0.0] | [0.0] |
| $\Gamma$ | $1.07^{+0.06}_{-0.03}$ | $1.24^{+0.03}_{-0.03}$ |
| $\chi^2$/dof | 0.91 (167.7/185) | 1.24 (458.7/367) |
| $P(H0)$ | 0.81 | $7.8 \times 10^{-4}$ |

### Broken power law ($E \geq 1.5$ keV)

| Parameter | Value in C03 | Value in X13 |
|-----------|---------------|---------------|
| $n_{H,\text{int}} \times 10^{20}$ cm$^{-2}$ | [0.0] | [0.0] |
| $\Gamma_{\text{soft}}$ | $0.97^{+0.08}_{-0.11}$ | $1.19^{+0.05}_{-0.05}$ |
| $\Gamma_{\text{hard}}$ | $1.50^{+0.64}_{-0.30}$ | $2.60^{+0.37}_{-0.29}$ |
| $E_{br}$ (keV) | $4.2^{+1.2}_{-1.5}$ | $5.45^{+0.39}_{-0.31}$ |
| $\chi^2$/dof | 0.87 (158.9/183) | 0.99 (361.6/365) |
| $P(H0)$ | 0.90 | 0.54 |

### Comptonization spectrum diskbb+comptt

| Parameter | Value in C03 | Value in X13 |
|-----------|---------------|---------------|
| $n_{H,\text{int}} \times 10^{20}$ cm$^{-2}$ | $0.0^{+1.0}_{-0.0}$ | $6.4^{+1.6}_{-1.6}$ |
| $kT_{\text{in}} \equiv kT_0$ (keV) | $0.20^{+0.08}_{-0.05}$ | $0.32^{+0.07}_{-0.07}$ |
| $N_{\text{bb}}$ | $0.0^{+0.0}_{-0.0}$ | 0.8 |
| $kT_{\text{e}}$ (keV) | $2.11^{+0.37}_{-0.23}$ | $1.67^{+0.20}_{-0.12}$ |
| $\Gamma$ | $11.7^{+1.2}_{-1.2}$ | $14.6^{+0.7}_{-1.6}$ |
| $\chi^2$/dof | 0.96 (247.1/258) | 1.03 (619.1/600) |
| $P(H0)$ | 0.68 | 0.29 |

| Parameter | Value in C03 | Value in X13 |
|-----------|---------------|---------------|
| $L_{0.3-10\text{keV}}$ (10$^{38}$ erg s$^{-1}$) | $3.5^{+0.1}_{-0.1}$ | $2.0^{+0.1}_{-0.1}$ |

Spectral fits to Chandra (C03) and XMM-Newton (X13) bright-state X-ray spectra, from 2003 and 2013, respectively. All errors are given at the 90% confidence level. $P(H0)$ is the null hypothesis probability. In all cases, we assume a fixed Galactic column density $n_H = 2.0 \times 10^{20}$ cm$^{-2}$ (tbabs model) in addition to a fitted intrinsic (NGC 7793 + local) absorption column. For the diskbb model, we assumed $f_{\text{in}} = 0.1$, $f_{\text{out}} = 1.2$, $f_{\text{out}} = 0.005$ and $\log(e_{\text{out}}) = 5.0$.

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