Super-Eddington Accretion onto the Galactic Ultraluminous X-Ray Pulsar Swift J0243.6+6124

Lian Tao1, Hua Feng2, Shuangnan Zhang1,3,4, Qingcui Bu1, Shu Zhang1, Jinlu Qu1, and Yue Zhang1,4

1 Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
2 Department of Engineering Physics and Center for Astrophysics, Tsinghua University, Beijing 100084, People’s Republic of China
3 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, People’s Republic of China
4 University of the Chinese Academy of Sciences, Beijing, People’s Republic of China

Received 2018 November 7; revised 2019 January 11; accepted 2019 January 25; published 2019 February 28

Abstract

We report on the spectral behavior of the first Galactic ultraluminous X-ray pulsar Swift J0243.6+6124 with NuSTAR observations during its 2017–2018 outburst. At sub-Eddington levels, the source spectrum is characterized by three emission components: from the accretion column, the hot spot, and a broad iron line. At super-Eddington levels, the iron line becomes more significant and blueshifted, and is argued to be associated with the ultrafast wind in the central funnel or jets. This source, if located in external galaxies, will appear like other ultraluminous pulsars.

Key words: accretion, accretion disks – magnetic fields – pulsars: individual (Swift J0243.6+6124) – stars: neutron – X-rays: binaries

1. Introduction

The physical processes for super-Eddington accretion onto compact objects are still unclear. Ultraluminous X-ray sources (ULXs), which are non-nuclear point-like X-ray sources with apparent luminosities above $\sim 10^{39}$ erg s$^{-1}$ (for a review see Kaaret et al. 2017), may be powered by super-Eddington accretion and are thus good targets for such studies (e.g., Middleton et al. 2015). Among ULXs, the ultraluminous pulsars (ULPs) are of particular interest because the compact object mass is well constrained (1–3 $M_\odot$). So far, four ULPs have been detected, including M82 X-2 (Bachetti et al. 2014), NGC 7793 P13 (Fürst et al. 2016; Israel et al. 2017b), NGC 5907 ULX1 (Israel et al. 2017a), and NGC 300 ULX1 (Carpano et al. 2018), with a period of $\sim 1$ s for the former three and $\sim 30$ s for NGC 300 ULX1. They all show a large spin-up rate, $\dot{\nu} \approx 10^{-10}$ Hz s$^{-1}$, which is at least one order of magnitude greater than that of ordinary accreting pulsars, e.g., SMC X-1 (Kahabka & Li 1999) and Cen X-3 (van der Klis et al. 1980). The high spin-up rate of ULPs may be driven by their high accretion rates (King et al. 2017).

Numerical simulations (Ohsuga & Mineshige 2011; Jiang et al. 2014; Sądowski & Narayan 2016) predict that super-Eddington accretion onto compact objects will launch nearly spherical, massive, optically thick outflows/winds, as well as optically thin ultrafast outflows (UFOs) near the axis. Analytical analysis for super-Eddington accretion also reveals that massive outflows are inevitable (Meier 1982; Poutanen et al. 2007; Shen et al. 2015, 2016). Blueshifted ($0.1$–$0.2c$) absorption lines are seen in the high signal-to-noise X-ray spectra of ULXs (e.g., Pinto et al. 2016, 2017; Walton et al. 2016), as direct evidence for the UFOs. The association of shock-ionized optical nebulae (Pakull & Mirioni 2003) with ULXs suggests the presence of the massive outflow interacting with the environment. The correlation between the line width and ionization level for broad emission lines in the optical spectra of ULXs is consistent with a wind origin (Fabrika et al. 2015). The soft excesses observed in the ULX spectra could be due to emission from the photosphere of the optically thick outflows (e.g., Middleton et al. 2015; Weng & Feng 2018). In addition to the uncollimated outflows, jets are also predicted by simulations under super-Eddington accretion (Ohsuga & Mineshige 2011; Narayan et al. 2017). SS 433 is believed to be accreting at a super-Eddington level and shows precessing and baryonic jets around 0.26$c$ (Fabrika 2004). The supersoft ULX M81 ULS-1 displays a varying ($0.1$–$0.2c$) H$\alpha$ emission line, which could be due to jets similar to those seen in SS 433 (Liu et al. 2015).

High quality spectroscopy is needed to test the models and simulation results, but is difficult for ULXs/ULPs due to their extragalactic distances. Swift J0243.6+6124 is a transient accreting pulsar in the Milky Way with a peak luminosity of $\sim 5 \times 10^{38}$ erg s$^{-1}$ (Tsygankov et al. 2018), exceeding the Eddington limit for a neutron star by a factor of $\sim 30$, during its outburst in 2017–2018 (Kennea et al. 2017), brighter than another Galactic Super-Eddington accretion source, SMC X-3 (Weng et al. 2017; Zhao et al. 2018). The source exhibits a spin period of $\sim 9.86$ s (Ge et al. 2017; Jenke & Wilson-Hodge 2017; Kennea et al. 2017) and a spin-up rate of $\sim 10^{-10}$ Hz s$^{-1}$ when $L_X \gtrsim 10^{37}$ erg s$^{-1}$ (Doroshenko et al. 2018), which are similar to those of extragalactic ULPs. This offers us an opportunity to study a ULP at a Galactic distance. Radio jets were observed during the outburst, which challenges the classical theory of jet formation with neutron stars (van den Eijnden et al. 2018), but is consistent with what is expected for super-Eddington, accretion as mentioned above.
Here, we focus on the spectral modeling of Swift J0243.6+6124 with the \textit{NuSTAR} data, trying to test and constrain the physics for super-Eddington accretion. We adopt a distance of 7 kpc to the source measured with \textit{Gaia} (Tsygankov et al. 2018; Wilson-Hodge et al. 2018).

2. Observations and Data Reduction

We collected five \textit{NuSTAR} (Harrison et al. 2013) observations during the 2017–2018 outburst of Swift J0243.6+6124 (Table 1). A very short observation (ObsID 90401308001) with an exposure time of 18 s was discarded. The times of the \textit{NuSTAR} observations were marked in Figure 1, on top of the \textit{Swift}/BAT \cite{Tsygankov2018} and \textit{Insight}-HXMT \cite{Zhang2014} light curves. The five \textit{NuSTAR} observations sampled the complete cycle of the outburst at different epochs, composing a treasure database for the study of ULPs.

The cleaned \textit{NuSTAR} event files are created using \textit{NuSTAR}-DAS pipeline 1.8.0 in HEASoft v6.22, with the \textit{NuSTAR} CALDB version 20180419. The peak flux of Swift J0243.6+6124 is up to \textasciitilde 8 Crab \cite{Tsygankov2018}, in which case some source events may be improperly discarded by a noise filter in nupipeline, resulting in an underestimate of the source flux \cite{Tsygankov2018}. Therefore, following the analysis guide, we first extracted the light curves in 1 s bins, and altered the filter in the four observations (except ObsID 90401308002) where the count rate exceeds 100 counts s$^{-1}$. This was done by setting the keyword \texttt{statusexpr} with an expression of “\texttt{STATUS\&=\&0000}\texttt{XXX0XXX0XX0000}” before the cleaned event files were generated. Then, the source events were extracted from a circular region centered at the source position with a radius of 180$''$. The background was estimated from a nearby source-free circular region. Energy spectra were binned to have at least 50 counts per bin.

3. Spectral Modeling and Results

The spectral fit was done in XSPEC v12.10.0e (Arnaud 1996). Following Bahramian et al. (2017) and Jaisawal et al. (2018), we first adopted a three-component model (model 1 = cutoffpl + bbodyrad + Gaussian) subject to interstellar absorption (tbabs). The three components are to account for emission from the accretion column, the thermal emission from the hot spot around the polar region, and the iron emission region, respectively. Model 1 gives an adequate fit to the two spectra in the low states, from the first and last observations, with model parameters consistent with those reported in Jaisawal et al. (2018) for ObsID 90302319002. For the remaining three observations, which were taken around the peak of the outburst when the luminosity was above the Eddington limit, model 1 is unable to fit the spectra successfully and a more complicated model is needed. Following the physical picture for super-Eddington accretion, where optically thick outflows may be launched (Zhou et al. 2015), we added two additional thermal components (model 2 = model 1 + bbodyrad + bbodyrad), respectively, to account for the thermal emission from the photosphere of the outflow and from the extended column. Moreover, for the two observations (ObsID 90302319004 and 90302319006) with the highest luminosities, an additional edge component is required near the iron K edge. The spectral parameters are listed in Table 2 and the model components are plotted in Figure 2.

A minor feature in the residuals near 6–7 keV for ObsIDs 90302319004 and 90302319006 may be seen. It is likely related to the asymmetry of the iron line, but is weak and will not influence our results here. In order to inspect the broad iron line, we removed the emission line and absorption edge components from the model, and plotted the residuals in Figure 3 to enhance the iron line feature.

4. Timing Analysis

The barycenter correction was applied before the light curves were binned to a time resolution of 100 ms. We searched the spin period using the \texttt{efsearch} task in \texttt{FTOOLS} and found that the spin period decreased from 9.8539 to 9.7933 s from the first to the last observation. For each observation, the pulse profile was obtained by folding the light curves with the \texttt{FTOOLS efold} task. The pulsed fraction are calculated in different energy bands (Figure 4), defined as \( \frac{F_{\text{max}} - F_{\text{min}}}{F_{\text{max}} + F_{\text{min}}} \), where \( F_{\text{max}} \) and \( F_{\text{min}} \) are maximum and minimum intensity, respectively. For the three observations at a super-Eddington level, the pulsed fraction increases with the increasing photon energy and accretion rate. For the remaining two observations, it peaks around 20 keV. The results in the low-energy bands are consistent with those obtained with \textit{NICER} data (Wilson-Hodge et al. 2018).

\begin{table}
\centering
\caption{\textit{NuSTAR} Observations Used in the Paper}
\begin{tabular}{llll}
\hline
ObsID & Date & Exposure & Count Rate (counts s$^{-1}$) \\
\hline
90302319002 & 2017 Oct 5 15:51:09 & 14277 & 122.78 ± 0.09 \\
90302319004 & 2017 Oct 31 07:21:09 & 1293 & 2700.3 ± 1.5 \\
90302319006 & 2017 Nov 10 02:31:09 & 676 & 4001 ± 2.0 \\
90302319008 & 2017 Dec 6 14:46:09 & 4589 & 959.5 ± 0.5 \\
90401308002 & 2018 Mar 10 12:21:09 & 27816 & 16.88 ± 0.03 \\
\hline
\end{tabular}
\end{table}

Note. Count rate is the net count rate of FPMA.
Table 2
Best-fit Models and Spectral Parameters

| Component            | Parameter | 90302319002 | 90302319004 | 90302319006 | 90302319008 | 90401308002 |
|----------------------|-----------|-------------|-------------|-------------|-------------|-------------|
| tbabs                | \( N_\text{H} (10^{23} \text{ cm}^{-2}) \) | 1.0 ± 0.2  | 0.6^{+2.3}_{-0.6} | 6^{+2}_{-0.5} | 2.4^{+1.0}_{-0.9} | 1.7 ± 0.5   |
| cutoffpl (column)   | \( \Gamma \)     | 1.11 ± 0.03 | 1.1^{+0.3}_{-0.4} | 1.4^{+0.3}_{-0.5} | 0.42 ± 0.15 | 1.21 ± 0.05 |
|                     | \( E_{\text{cut}} \) (keV) | 24.5 ± 0.9 | 20^{+1.3}_{-1.2} | 26^{+1.8}_{-1.5} | 17.4 ± 1.3 | 25.2^{+1.8}_{-1.6} |
|                     | \( N_{\text{cut}} \) (photons keV^{-1} cm^{-2} s^{-1}) | 0.28^{+0.03}_{-0.02} | 4 ± 3 | 14^{+0.9}_{-0.7} | 0.40 ± 0.17 | 0.052 ± 0.006 |
| bbodyrad (hot spot) | \( T_{\text{bb}} \) (keV) | 3.06 ± 0.03 | 4.5 ± 0.4 | 4.4^{+0.3}_{-0.2} | 4.43 ± 0.18 | 2.21 ± 0.06 |
|                     | \( R_{\text{bb}} \) (km) | 0.99^{+0.015}_{-0.014} | 1.4 ± 0.3 | 1.8^{+0.3}_{-0.4} | 1.28 ± 0.13 | 0.57 ± 0.03 |
| bbodyrad (column top)| \( T_{\text{bb}} \) (keV) | ... | 1.46 ± 0.07 | 1.40 ± 0.04 | 1.435 ± 0.017 | ... |
|                     | \( R_{\text{bb}} \) (km) | ... | 20 ± 3 | 27 ± 4 | 12.5 ± 0.4 | ... |
| bbodyrad (outflow)  | \( T_{\text{bb}} \) (keV) | ... | 0.57^{+0.11}_{-0.09} | 0.42 ± 0.08 | 0.481 ± 0.014 | ... |
|                     | \( R_{\text{bb}} \) (km) | ... | 120^{+170}_{-30} | 500^{+200}_{-100} | 10^{+100}_{-14} | ... |
| \( L_{\text{bb}} \) (10^{38} \text{ erg s}^{-1}) | ... | 1.88 ± 0.15 | 8 ± 6 | 0.82 ± 0.17 | ... |
| Gaussian (iron)     | \( E_{\gamma} \) (keV) | 6.44 ± 0.04 | 6.80^{+0.16}_{-0.20} | 6.99^{+0.14}_{-0.17} | 6.476 ± 0.017 | 6.33 ± 0.05 |
|                     | \( \sigma \) (keV) | 0.45^{+0.07}_{-0.06} | 1.26^{+0.11}_{-0.14} | 1.14^{+0.10}_{-0.14} | 0.27 ± 0.03 | 0.34^{+0.17}_{-0.14} |
|                     | \( \text{EW} \) (keV) | 0.080^{+0.003}_{-0.009} | 0.51^{+0.01}_{-0.10} | 0.36 ± 0.16 | 0.058±0.009 | 0.076 ± 0.012 |
| edge (iron)         | \( E_{\text{edge}} \) (keV) | ... | 7.027^{+0.013}_{-0.025} | 6.99 ± 0.05 | ... | ... |
|                     | \( \tau \) | ... | 0.156^{+0.013}_{-0.021} | 0.097^{+0.003}_{-0.009} | ... | ... |

Note. \( N_{\text{cut}} \) is the cutoffpl normalization at 1 keV; \( F_{3-79 \text{ keV}} \) is the observed flux of FPMA and \( L_{0.1-100 \text{ keV}} \) is the absorption-corrected luminosity. All errors are quoted at the 90% confidence level.

\( F_{3-79 \text{ keV}} \) (erg cm\(^{-2}\) s\(^{-1}\)) | 8.73 \times 10^{-9} | 1.55 \times 10^{-7} | 2.27 \times 10^{-7} | 0.74 \times 10^{-7} | 1.14 \times 10^{-9} |
---|---|---|---|---|---|
\( L_{0.1-100 \text{ keV}} \) (erg s\(^{-1}\)) | 6.01 \times 10^{37} | 1.22 \times 10^{39} | 2.67 \times 10^{39} | 0.55 \times 10^{39} | 0.83 \times 10^{37} |

\( \chi^2/\text{dof} \) | 2084.7/1987 | 2207.1/1986 | 2040.5/1990 | 2811.3/2479 | 1476.9/1476 |

\textbf{Figure 2}. Top: energy spectra and model components. Bottom panels: spectral residuals with respect to the best-fit model.

\textbf{5. Discussion}

Swift J0243.6+6124 is the first known ULP in our Galaxy, enabling a close look at the properties of the same kind. In the...
following, we will interpret the spectral results in a scenario consistent with the super-Eddington accretion. A schematic drawing of the physical picture can be found in Figure 5.

When the source accretes at a sub-Eddington level, only three emission components were detected: from the accretion column, the iron line, and the hot spot (blackbody, $T_{bb} = 2–3$ keV, $R_{bb} = 0.6–1.0$ km). When the luminosity is in excess of the Eddington limit, two additional thermal components, sometimes along with an absorption edge, are needed to fit the spectra. In these cases, the hot spots become even hotter, with a temperature of about 4.5 keV, but the radius remains around 1 km. One of the new thermal components has a temperature of around 1.5 keV and a radius of 10–20 km. This could be explained by emission from the top of the accretion column at the super-Eddington level, where the accretion column may grow to a size comparable to the neutron star radius, with a temperature gradient, from 4.5 keV at the base to 1.5 keV at the top (Mushotzky et al. 2015). A two-temperature blackbody is perhaps an approximation of the thermal emission from the base to the top.

The other new thermal component has a temperature of about 0.5–0.6 keV with a radius of 110–120 km, or a blackbody luminosity of about $(1–2) \times 10^{38}$ erg s$^{-1}$. The blackbody luminosity stays constant between observations. We note that the blackbody luminosity derived from ObsID 90302319006 is consistent with this value but cannot be well constrained. The luminosity of this thermal component is coincident with the Eddington limit of a neutron star. This can be self-consistently explained if the thermal emission arises from the photosphere of the optically thick outflow driven by super-Eddington accretion. According to the super-Eddington accretion models, the outflow is launched near the radius where the Eddington limit is approached (Shakura & Sunyaev 1973; Meier 1982; Poutanen et al. 2007; Shen et al. 2015, 2016). If the wind launch radius is above the photon trapping radius, the radiation and materials in the wind will stay in local thermodynamic equilibrium and the radiative luminosity will stay constant at the Eddington limit. Thus, the massive, optically thick wind under super-Eddington accretion is thought to be Eddington-limited, which was found to be consistent with observations for supersoft ULXs (Feng et al. 2016; Urquhart & Soria 2016; Zhou et al. 2019). Thus, the thermal component detected here can be naturally explained as a signature of the optically thick outflow. This may shed light on the strength of the dipole magnetic field (Mushotzky et al. 2019).

Following the outflow model of Meier (1982; see more details in Zhou et al. 2019), assuming a $1.4 M_\odot$ neutron star, we found that one needs a mass accretion rate of $\dot{m} = (60–80) M/M_{\text{Edd}}$ to match the observed blackbody temperature ($T_{bb} \approx 0.5–0.6$ keV), where $M_{\text{Edd}} = L_{\text{Edd}}/0.1 c^2$ is the critical mass accretion rate needed to power the Eddington limit. The model predicts a scattering optical depth ($\tau_{\text{sc}}$) at the photosphere of around 200. In this case, the physical radius of the photosphere is $R_\star \approx R_{bb} \sqrt{\tau_{\text{sc}}} \approx 1.6 \times 10^3$ km. The model assumes that the wind is launched at a radius ($R_1$) near the advective radius of a slim disk, $R_1 \approx 750–1000$ km. The accretion disk is truncated by the magnetic fields at $R_M = (3.3 \times 10^2)$ km $B_\perp^{1/2} L_{\text{Edd}}^{1/2} R_\star^{1/2} m_M^{1/4}$ (Ghosh & Lamb 1979). If the magnetic field of Swift J0243.6+6124 is $10^5$ G (Doroshenko et al. 2018; Wilson-Hodge et al. 2018), one gets $R_M \approx 1 \times 10^3$ km with typical values for other parameters; if we follow Tsygankov et al. (2018) and use the upper limit for the magnetic fields ($B < 6.2 \times 10^{12}$ G) derived from the undetected propeller effect, one gets $R_M < 900$ km. We note that these estimates are precise only to the order of magnitude, but it suggests that the optically thick wind may have been launched at a position close to the Alfvén radius.

The broad iron emission line is significant in the spectra of Swift J0243.6+6124. Similar features have been frequently observed in low-mass neutron star X-ray binaries such as Serpens X-1 (Bhattacharyya & Strohmayer 2007), 4U 1820-30, GX 349+2 (Cackett et al. 2008), and GX 17+2 (Ludlam et al. 2017). None of the extragalactic ULPs shows such a feature. We ran simulations and found that this is due to observational effects. If one takes the spectral model of Swift J0243.6+6124 in the outburst peak, where the iron line is most prominent, renormalizes the X-ray luminosity to $10^{40}$ erg s$^{-1}$ in 0.3–10 keV, and places the source at a distance of 1.9 Mpc as for the closest ULP (NGC 300 ULX), the iron line is not detectable with an XMM-Newton observation even with an exposure of 100 ks.
As one can see from Figure 3, the line strength is correlated with the X-ray luminosity, suggesting that the line may be generated in association with the winds or jets driven by super-Eddington accretion. In the first observation, the peak energy is consistent with 6.4 keV expected for the K_α emission from Fe I; in the second and third observations during the outburst peak, it is higher than 6.4 keV but less than the 6.7 keV expected for Fe XXV, which is detected in the jets of SS 433 (Kotani et al. 1994; Marshall et al. 2002); in the fourth observation, it seems to have double peaks or a flat top, but the evidence is marginal; in the last observation, a narrow component below 6.4 keV seems to stand out above a broad component. The Fe absorption edge appears only in the most luminous states, implying that they are associated with the optically thin part of the wind, perhaps the UFOs in the funnel.

One possibility is that the materials that have iron emission are mostly neutral at relatively low luminosities, but the ionization level increases toward high luminosities. However, this cannot explain the fact that the narrow component in the last observation is below the neutral iron K_α energy. A more likely interpretation is that the narrow iron emission originates in the jets. The redshifted narrow line in the last observation arises from the receding jet, while the possibly double-peaked feature in the fourth observation is due to both approaching and receding jets. In the super-Eddington regime, the UFO in the central funnel may have a speed close to the jet (0.1–0.2c) and produce a velocity-broadened, blueshifted iron line, in line with our observations. These speculations may be tested with future high-resolution spectroscopic observations.

In our interpretation, the emission from the accretion column will cause X-ray pulsations, mainly from the cutoff power-law component. The thermal emission from the hot spot and the column is also modulated but perhaps at a lower degree. Emission from the outflow should not be modulated by the rotation of the neutron star. As the cutoff power-law component dominates toward high energies, the pulsed fraction is expected to be stronger at higher energies, which is in good agreement with measurements during the super-Eddington level. However, when the source is at sub-Eddington, why the pulsed fraction drops above 20 keV is puzzling, which may suggest a geometry different from that of super-Eddington accretion. In this paper, we mainly focus on the spectral properties. Learning how to link the spectral behavior to the timing properties quantitatively requires in-depth investigations.

An interesting question is whether or not this source appears like extragalactic ULPs. When Swift J0243.6+6124 is in the ultraluminous phase (in the second and third observations), we extract a short-exposure spectrum by randomly selecting part of the photons as if the source has a luminosity of 10^{40} erg s^{-1} in 0.1–100 keV, observed with an exposure of 100 ks at a distance of 1.9 Mpc (distance to the nearest extragalactic ULP in NGC 300). The spectra were then fit with two models that have been used for ULPs, a power law with high energy cutoff (Pintore et al. 2017), and a three-component model, cool disk blackbody + hot blackbody + cutoff power law (Walton et al. 2018). The blackbody component used in Pintore et al. (2017) has a temperature too low to be detectable with NuSTAR. To be consistent with Walton et al. (2018), we froze the power-law photon index at 0.5. Both models provide a good fit, although the first model results in some residuals around 5–10 keV; see Table 3 for best-fit parameters. The derived parameters are consistent with those obtained for extragalactic ULPs, except the e-folding energy is higher for Swift J0243.6+6124, suggesting a higher temperature. In the second model, the high temperature blackbody could arise from the accretion column and the cool thermal component (though fitted with a disk blackbody) is likely from the outflow. We note that the hot spot and the iron line component cannot be significantly detected in the spectra.

To summarize, Swift J0243.6+6124 has offered us a unique opportunity to have a close look at the super-Eddington accretion onto a neutron star. In this paper, we proposed a physical picture that can self-consistently explain the spectral behavior of the source, suggesting that the massive, optically thick outflows can be launched in magnetized systems under super-Eddington accretion.

We thank the anonymous referee, Diego Altamirano, and Can GÜNGÖR for useful comments. L.T. acknowledges funding support from the National Natural Science Foundation of China (NSFC) under grants No. U1838115 and U1838201, the CAS Pioneer Hundred Talent Program Y8291130K2, and the Scientific and technological innovation project of IHEP Y7515570U1. H.F. acknowledges funding support from the National Key R&D Program of China (grants No. 2016YFA040080X and 2018YFA0404502), and the National Natural Science Foundation of China under grants No. 11633003 and 11821303. S.Z. is thankful for support from the National Key R&D Program of China (2016YFA040080X) and the Chinese NSFC grants U1838201, 11733009, and 2018YFA0404502.

Facilities: NuSTAR, Insight-HXMT, Swift.

### Table 3

| Component       | Parameter | 90302319004 | 90302319006 |
|-----------------|-----------|-------------|-------------|
| tbabs           | N_H (10^{22} cm^{-2}) | 4.3±0.9 | 6.0±1.3 |
| highcut         | E_0 (keV)  | 6.6±0.6 | 6.4±0.6 |
|                 | E_1 (keV)  | 63±29 | 43±19 |
| power law       | Γ         | 2.10±0.07 | 2.01±0.10 |
|                 | χ^2/dof   | 654.0/531 | 412.8/431 |
| tbabs           | N_H (10^{22} cm^{-2}) | 5 | 5 |
| diskbb          | T_{in} (keV) | 0.47±0.05 | 0.37±0.09 |
|                 | R_{in} (km) | 460±380 | 1300±600 |
|                 | R_{mb} (km) | 281±13 | 34±2 |
| cutoffpl        | E_{cut} (keV) | 12.6±7 | 11.8±.9 |
|                 | χ^2/dof   | 555.9/530 | 353.8/430 |

**Notes.**

* N_H is hard to constrain and fix at 5×10^{22} cm^{-2}.  
* Following Walton et al. (2018), R_{in} is obtained assuming cos θ = f_{cut} = 1.  
* All errors are quoted at the 90% confidence level.

**ORCID iDs**

Lian Tao  [https://orcid.org/0000-0002-2705-4338](https://orcid.org/0000-0002-2705-4338)  
Hua Feng  [https://orcid.org/0000-0001-7584-6236](https://orcid.org/0000-0001-7584-6236)  
Qingcui Bu  [https://orcid.org/0000-0001-5238-3988](https://orcid.org/0000-0001-5238-3988)
References

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems, ed. G. H. Jacoby & J. Barnes (San Francisco, CA: ASP), 17

Bachetti, M., Harrison, F. A., Walton, D. J., et al. 2014, Natur, 514, 202

Brahmanian, A., Kenna, J. A., & Shaw, A. W. 2017, ATel, 10866, 1

Bhattarcharya, S., & Strohmayer, T. E. 2007, ApJL, 664, L103

Cackett, E. M., Miller, J. M., Bhattarcharya, S., et al. 2008, ApJ, 674, 415

Carpano, S., Haberl, F., Maitra, C., & Vasilopoulos, G. 2018, MNRAS, 476, L45

Doroshenko, V., Tsygankov, S., & Santangelo, A. 2018, A&ArSS, 613, A19

Fabrika, S. 2004, ASPRv, 12, 1

Fabrika, S., Ueda, Y., Vinokurov, A., Sholukhova, O., & Shidatsu, M. 2015, NatPh, 11, 551

Feng, H., Tao, L., Kaaret, P., & Grisé, F. 2016, ApJ, 831, 117

Fürst, F., Walton, D. J., Harrison, F. A., et al. 2016, ApJL, 831, L14

Ge, M., Zhang, S., Lu, F., et al. 2017, ATel, 10907, 1

Ghosh, P., & Lamb, F. K. 1979, ApJ, 234, 296

Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103

Israel, G. L., Belfiore, A., Stella, L., et al. 2017a, Sci, 355, 817

Israel, G. L., Papitto, A., Esposito, P., et al. 2017b, MNRAS, 466, L48

Jaisawal, G. K., Naik, S., & Chenevez, J. 2018, MNRAS, 474, 4432

Jenke, P., & Wilson-Hodge, C. A. 2017, ATel, 10812, 1

Jiang, Y.-F., Stone, J. M., & Davis, S. W. 2014, ApJ, 796, 106

Kaaret, P., Feng, H., & Roberts, T. P. 2017, ARA&A, 55, 303

Kahabka, P., & Li, X.-D. 1999, A&A, 345, 117

Kennea, J. A., Lien, A. Y., Krimm, H. A., Cenko, S. B., & Siegel, M. H. 2017, ATel, 10809, 1

King, A., Lasota, J.-P., & Kluzniak, W. 2017, MNRAS, 468, L59

Kotani, T., Kawai, N., Aoki, T., et al. 1994, PASJ, 46, L147

Liu, J.-F., Bai, Y., Wang, S., et al. 2015, Natur, 528, 108

Ludlam, R. M., Miller, J. M., Bachetti, M., et al. 2017, ApJ, 836, 140

Marshall, H. L., Canizares, C. R., & Schulz, N. S. 2002, ApJ, 564, 941

Meier, D. L. 1982, ApJ, 256, 681

Middleton, M. J., Heil, L., Pintore, F., Walton, D. J., & Roberts, T. P. 2015, MNRAS, 447, 3243

Mushtukov, A. A., Ingram, A., Middleton, M., Nagirner, D. I., & van der Klis, M. 2019, MNRAS, 484, 687

Mushtukov, A. A., Suleimanov, V. F., Tsygankov, S. S., & Poutanen, J. 2015, MNRAS, 454, 2539

Narayan, R., Sadowski, A., & Soria, R. 2017, MNRAS, 469, 2997

Ohsuga, K., & Mineshige, S. 2011, ApJ, 736, 2

Pakull, M. W., & Mirioni, L. 2003, RMxAC, 15, 197

Pinto, C., Alston, W., Soria, R., et al. 2017, MNRAS, 468, 2865

Pinto, C., Middleton, M. J., & Fabian, A. C. 2016, Natur, 533, 64

Pintore, F., Zampieri, L., Stella, L., et al. 2017, ApJ, 836, 113

Poutanen, J., Lipunova, G., Fabrika, S., Butkevich, A. G., & Abolmasov, P. 2007, MNRAS, 377, 1187

Sadowski, A., & Narayan, R. 2016, MNRAS, 456, 3929

Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337

Shen, R.-F., Barniol Duran, R., Nakar, E., & Piran, T. 2015, MNRAS, 447, L60

Shen, R.-F., Nakar, E., & Piran, T. 2016, MNRAS, 459, 171

Tsygankov, S. S., Doroshenko, V., Mushtukov, A. A., Lutovinov, A. A., & Poutanen, J. 2018, MNRAS, 479, L134

Urquhart, R., & Soria, R. 2016, MNRAS, 456, 1859

van den Eijnden, J., Degenaar, N., Russell, T. D., et al. 2018, Natur, 562, 233

van der Klis, M., Bonnet-Bidaud, J. M., & Robba, N. R. 1980, A&A, 88, 8

Walton, D. J., Fürst, F., Heida, M., et al. 2018, ApJ, 856, 128

Walton, D. J., Middleton, M. J., Pinto, C., et al. 2016, ApJL, 826, L26

Weng, S.-S., & Feng, H. 2018, ApJ, 853, 115

Weng, S.-S., Ge, M.-Y., Zhao, H.-H., et al. 2017, ApJ, 843, 69

Wilson-Hodge, C. A., Malacaria, C., Jenke, P. A., et al. 2018, ApJ, 863, 9

Zhang, S., Lu, F. J., Zhang, S. N., & Li, T. P. 2014, Proc. SPIE, 9144, 914421

Zhao, H.-H., Weng, S.-S., Ge, M.-Y., Bian, W.-H., & Yuan, Q.-R. 2018, ApSS, 363, 21

Zhou, Y., Feng, H., Ho, L. C., & Yao, Y. 2019, ApJ, 871, 115