Disappearance of the Fe Kα emission line in Ultra Compact X-ray Binaries 4U 1543−624 and Swift J1756.9−2508

Filippos Koliopanos1,2*, Georgios Vasilopoulos3, Sebastien Guillot1,2,4 and Natalie Webb1,2

1 Université de Toulouse; UPS-OMP; IRAP, Toulouse, France
2 CNRS, IRAP, 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France
3 Department of Astronomy, Yale University, PO Box 208101, New Haven, CT 06520-8101, USA
4 CNES, IRAP, 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France

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ABSTRACT
We investigate the long-term variability of the Kα line of iron in the spectra of two Ultra Compact X-ray Sources (UCXBs) with C/O-rich donors. We revisit archival observations by five different X-ray telescopes, over a ∼twenty year period. Adopting physically motivated models for the spectral continuum, we probe the long-term evolution of the source emission in a self-consistent manner enabling physical interpretation of potential variability primary X-ray emission continuum and/or any emission lines from reflection off the accretion disk. We find that the spectral shape and flux of the source emission (for both objects) has remained almost constant throughout all the observations, displaying only minor variability in some spectral parameters and the source flux (largest variation is a ∼25% drop in the flux of Swift J1756.9−2508). We note a striking variability of the Fe Kα line which fluctuates from a notable equivalent width of ∼66-100 eV in 4U 1543−624 and ∼170 eV in Swift J1756.9−2508, to non-detections with upper limits of 2-8 eV. We argue that the disappearance of the iron line is due to the screening of the Fe Kα line by the overabundant oxygen in the C/O-rich UCXBs. This effect is cancelled when oxygen becomes fully ionized in the inner disk region, resulting in the variability of the Fe Kα line in an otherwise unaltered spectral shape. This finding supports earlier predictions on the consequences of H-poor, C/O-rich accretion disk on reflection induced fluorescent lines in the spectra of UCXBs.

Key words: Keywords from the MNRAS website

1 INTRODUCTION

Ultra compact X-ray binaries (UCXBs) are accreting binary systems, defined by their very short (less than 1hr) orbital periods. Their periods suggest such tight orbits that a main sequence star cannot fit (e.g., Rappaport & Joss 1984; Nelson, Rappaport & Joss 1986). Evolutionary scenarios and observational indications indicate that UCXBs are comprised of a Roche lobe filling white dwarf or helium star that is accreting material on to neutron star (e.g., Tutukov & Yungelson 1993; Iben et al. 1995; Verbunt & van den Heuvel 1995; Deloye & Bildsten 2003; Deloye et al. 2005). Depending on the formation paths of UCXBs – which may or may not include a common envelope phase with their donor star – UCXBs can have a variety of donors, ranging from He stars or WDs to C/O and O/Ne/Mg WDs (e.g., Savonije et al. 1986; Podsiadlowski et al. 2002; Yungelson et al. 2002; Bildsten & Deloye 2004). For simplicity UCXBs are often divided into two main categories: He-rich and He-poor, depending on the donor composition. Since divergent UCXB formation paths lead to degenerate donors of the same mass-scale, determining the chemical composition of the disk (and therefore the donor star) in these sources is a crucial step towards constraining their formation history. Furthermore, UCXBs, offer a unique op-
portunity to study accretion of hydrogen-poor matter onto compact objects.

The non-solar abundance of the accreting material in UCXBs a can have a profound effect on the emission line spectrum of UCXBs in both the optical (He, C, or O lines, e.g., Nelemans et al. 2004; Werner et al. 2006; Nelemans et al. 2006) and the X-ray wavelengths (primarily in the form of C and O Kα lines, e.g., Juett et al. 2001; Juett & Chakrabarty 2003; Madej et al. 2010). Nevertheless, due to the very faint optical counterparts of UCXBs (V-band absolute magnitudes ≳5) but also due to the increased interstellar absorption in the < 1 keV range of the X-ray spectrum the detection of C and O emission lines is often considerably difficult. In a relatively recent theoretical study, Koliopanos et al. (2013) demonstrated that the iron Kα line located at 6.4 keV (and therefore is not affected by interstellar absorption) can be used as an indirect method for determining the chemical composition of the accretion disk and donor star in UCXBs.

More specifically for moderately luminous sources (Lx < a few 10^{37} ergs s^{-1}) a strong suppression of the Fe Kα line was predicted in the case of a C/O or O/Ne/Mg WD donor, translating to a more than tenfold decrease of the equivalent width (EW) of the line. On the other hand, in the case of He-rich disks, the iron line remains unaffected with an EW in the same range as “standard” X-ray binaries (XRBs) with hydrogen rich donors. Observational analysis of five well-known UCXB sources corroborated these predictions (Koliopanos et al. 2014). In addition to the above predictions the Koliopanos et al. (2013) indicated that the screening effect is decidedly linked to the ionization state of oxygen and (to a second degree) carbon. The authors further demonstrated that – given some specific assumptions – the ionization state of C and O in the disk and subsequently the presence or absence of the prominent Fe Kα line is luminosity dependent. In this paper we report on the behavior of two known UCXBs, which appear to exhibit the iron line variability, predicted by Koliopanos et al. (2013).

4U 1543−624 is a well known UCXB which most likely hosts a C/O or Ne-rich WD donor (e.g., Juett et al. 2001). Discovered by the UHURU telescope (Jones 1977), it was classified as an UCXBs after Wang & Chakrabarty (2004) established a period of P=18.2 minutes, based on optical light curves. 4U 1543−624 is a persistent X-ray source with a stable, moderately bright emission since its discovery. It has been observed by most major X-ray observatories, including BEPPOSAX (Farinelli et al. 2003), ASCA and RXTE (Schultz 2003) as well as Chandra and XMM-Newton (Juett et al. 2001; Juett & Chakrabarty 2003; Madej & Jonker 2011; Madej et al. 2014) and more recently NICER (this paper and Ludlam et al. 2019). The X-ray continuum of the source has been modeled using a variety of different models including thermal and non-thermal components leading to different interpretations for its physical origin. Furthermore, a pronounced emission line centered at ~0.7 keV has been detected by both the XMM-Newton RGS and the Chandra HETG spectrometers. The emission line has been attributed to reflection of hard X-rays from a C/O-rich disk (most prominent being the OVII Lyα line, e.g., Juett & Chakrabarty 2003; Madej & Jonker 2011; Madej et al. 2014). The presence of the iron Kα line – usually detected in the spectra of X-ray binaries – has been much more dubious. The line was reported in BEPPOSAX and RXTE but was not present in ASCA spectra (Juett et al. 2001; Schultz 2003). Its potential presence has been tentatively claimed in the XMM-Newton spectra (Madej & Jonker 2011; Madej et al. 2014) but not in Chandra (Juett & Chakrabarty 2003). More recently, Ludlam et al. (2019) presented a thorough analysis of X-ray and radio observations of 4U 1543−624 during an enhanced accretion episode in 2017.

Swift J1756.9−2508 is an LMXB located in the direction of the Galactic bulge. It was discovered in 2007 during an X-ray outburst observed by the Swift-BAT. Follow up observations by RXTE identified the source as an UCXB (P_{out}~54.7 min) with a millisecond pulsar (Krimm et al. 2007). The transient source was again detected by the Swift-BAT and RXTE PCA during a second outburst in 2009 and more recently in 2018, when it was observed by Swift/XRT, XMM-Newton, NuSTAR and NICER. The multiple observations spanning more than a decade allowed the accurate study of the orbital evolution of the source (Patruno et al. 2010; Sanna et al. 2018; Bult et al. 2018), which in turn indicated the strength of the NS magnetic field at ~2×10^{10} G (Sanna et al. 2018). No type-I X-ray bursts were detected during any of the outbursts of Swift J1756.9−2508.

In this paper we revisit observations of 4U 1543−624 and Swift J1756.9−2508 at different epochs, focusing our analysis on the shape of the spectral continuum and the presence or absence of the iron emission line. More specifically we examine observations of 4U 1543−624 between 1997 and 2001 as well as its unusually bright 2017 outburst (4U 1543−624 is a persistent source, which entered a remarkably bright phase on Sept. 2017, Miller et al. 2017). For the transient source Swift J1756.9−2508 we study and compare its two outbursts of 2009 and 2018. We demonstrate that the X-ray spectrum of both sources has more or less the same shape through the years, which can be modeled using simple but physically motivated models. More importantly, we show that the flux of the Fe Kα emission detected on top of the spectrum continuum is variable by more than an order of magnitude. We discuss this behavior in the context of our 2013 prediction for Fe line variability in C/O-rich UCXBs and utilize our findings to further scrutinize and extend our initial hypothesis.

2 OBSERVATIONS, DATA ANALYSIS AND RESULTS

In this work we revisit archival 1997 RXTE, 2000 Chandra High Energy Transmission Grating (HETG), 2001 XMM-Newton and 2017 NICER observations of 4U 1543−624 and 2009 RXTE and 2017 XMM-Newton/NuSTAR observations of Swift J1756.9−2508. Details of the observations are tabulated in Table 1. We note that in the case of the RXTE and NICER observations there are multiple observations within a period of several days during the source outburst. We have
reviewed all available observations and selected those presented Table 1 based on their higher number of registered counts. We have verified that within all data sets the source was observed in the same spectral state. Analysis of the source spectra was carried out using the XSPEC X-ray spectral fitting package, Version 12.9.1 (Arnaud 1996).

2.1 Spectral hardening

In this analysis we pay additional attention to the physical properties inferred from the best fit parameters of thermal models used to probe the accretion disk and NS surface emission. We are interested the ionization state of the optically thick matter, while ensuring that the derived quantities are sensible in the context of accreting low magnetic field (low-B) NSs (i.e., temperature and inner disk radius commensurate with the characteristics of the accretor). For this reason it is important to take into account the effects of very high temperature (≥10^6 K) on the spectral shape of the thermal emission.

More specifically, with increasing temperature the thermal emission in X-ray astrophysical sources, is expected to diverge from the prototypical Planck spectrum, or the multi-color disk black body (MCD) emission (e.g., Mitsuda et al. 1984). Given the high (≥ 1 keV) temperatures of the hot thermal component in both thermal components, it is expected that electron scattering will have a significant effect on the resulting spectrum, as scattering becomes comparable to free-free absorption. Therefore, the actual emission will be radiated as a “diluted” black-body, which when modeled using a prototypical thermal model like diskbb or bbodyrad will result in temperature and radius estimations which will deviate from their “true” values. This issue is commonly addressed by considering a correction factor (f_col) that approximately accounts for the spectral modification (London et al. 1986; Lapidus et al. 1986; Shimura & Takahara 1995). This factor is often referred to as a color correction factor and detailed calculations, combined with multiple observations have demonstrated that it depends weakly on the size of the emitting region and the mass accretion rate (e.g., Shimura & Takahara 1995). Therefore in the 1st approximation it can be considered independent of these parameters and its value is estimated between ~ 1.5 and ~2.1 (e.g., Zimmerman et al. 2005, and references therein). The color correction factor affects both the temperature and normalization of the thermal models (i.e. diskbb and bbodyrad), with the corrected values given by

\[
T_{\text{cor}} = \frac{T}{f_{\text{col}}} \quad (1)
\]

and

\[
R_{\text{in}} = R_{\text{in}} f_{\text{col}}^2 \quad (2)
\]

where \(T\) is the temperature of the MCD component and \(R_{\text{in}}\) is the inner radius. In the following analysis we present all best fit values without correcting for the expected spectral hardening (i.e. \(f_{\text{col}} = 1.0\)); the effects of a more realistic value of \(f_{\text{col}}\) ~ 1.8 on the best-fit estimated values of disk temperature and inner radius are discussed in Section 3.

2.2 X-ray spectroscopy of 4U 1543-624

2.2.1 XMM-Newton April 2001 observation

\(XMM-Newton\) observed 4U1543−624 in April of 2001. All onboard instruments were operational. Namely, MOS1 and pn were operating in Timing Mode and MOS2 in Small Window Mode. All detectors had the Medium optical blocking filter on. In Timing mode data are registered in one dimension, along the column axis, which results in significantly shorter CCD readout time (0.06 ms for Timing mode, instead of 5.7 ms of the Small Window mode). In addition to increased time resolution the use of Timing mode, may protect observations of bright sources from

\[\text{Iron Kα line variability in UCXBs}\]

![Normalized counts vs. energy and ratio of the data to the continuum model for the 2001 Chandra observation. The data have been re-binned for clarity; the 1-10 keV energy range is shown.](image1)

![Normalized counts vs. energy and ratio of the data to the continuum model for the 2000 Chandra observation. The data have been re-binned for clarity; the 1-10 keV energy range is shown.](image2)

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Spectral extraction and analysis.

Spectra from all detectors were extracted using the latest XMM-Newton Data Analysis software SAS, version 15.0.0, and using the calibration files released\(^3\) by May 12, 2016. All observations were checked for high background flaring activity. To this end, we extracted high energy light curves (E>10 keV for MOS and 10≤E<12 keV for pn) with a 100 s bin size. A review of the lightcurves revealed no evidence of high energy flares in any of the detectors. The spectral extraction was done using SAS task evselect, with the standard filtering flags \((\#XMMEA\_EP \&\& \text{PATTERN}\leq4\) for pn and \#XMMEA\_EM \&\& \text{PATTERN}\leq12\) for MOS). SAS tasks rmfgen and arfgen were used to create the redistribution matrix and ancillary file. MOS2 data where suffering from pile-up and for this reason they were rejected. Furthermore, because the effective area of pn at ∼7 keV is approximately five times higher than that of MOS and since the main interest of this work lies in this energy range, we opted to only use the pn data for our analysis. 4U 1543−624 is known to exhibit a complex emission and absorption-like spectrum below 1 keV, as well as pronounced absorption edges, which are attributed to fluorescent emission and/or absorption from highly non-solar C/O or O/Ne/Mg-rich material transferred onto the NS by its degenerate donor (e.g., Juett et al. 2001; Juett & Chakrabarty 2003; Madej & Jonker 2011). The spectral models described in this section were applied to the entire energy range available from all detectors and we confirm the presence of soft emission-like features consistent with highly ionized oxygen. The emission-like feature is presented in Figure 1 for the Chandra observation of 4U 1543−624 (i.e., normalized counts and data-to-model ratio vs energy, without accounting for the ∼0.68 keV emission line reported by previous authors) and in Figure 2 for the XMM-Newton data where the feature has been modelled with a Gaussian emission line. Nevertheless, the analysis of these features is not the focus of our study and since ignoring the energy channels below 1 keV simplifies our analysis without affecting our parameter estimations, all tabulated best-fit values are for the spectral analysis of energy channels above 1 keV. For a detailed study of the atomic features in the low energy part of the spectrum of 4U 1543−624, we refer the reader to the works of Juett & Chakrabarty (2003), Madej & Jonker (2011) and most recently Ludlam et al. (2019).

We fit the 1–10 keV spectral continuum with a combination of absorbed black body (xspec model bbodyrad) and disk black body (xspec model diskbb) components. The interstellar absorption was modeled using the improved version of the tbabs code\(^4\) by Wilms et al. (2000). The hydrogen column density (nH) was frozen at the value provided by the HEASARC nH tool (HI4PI Collaboration et al. 2016). The fit yields a reduced \(\chi^2\) value of 1.04 for 1858/1795 dof, and the data-to-model ratio plot does not indicate emission-like residuals in the entire 1–10 keV region (Figure 3). Temperature of the disk black body is \(kT_{\text{in}}\sim0.65\) keV and the black body temperature is \(kT_{\text{BB}}\sim1.53\) keV. There is no evidence of iron Kα emission, with a 1σ upper limit of 2.68 eV on the EW of the line. The source luminosity, extrapolated in the 0.50–30 keV range, is \(\approx 5.1 \times 10^{36}\) erg/s, for a distance of 7 kpc (Wang & Chakrabarty 2004). All values of the best fit parameters are presented in Table 2.

\(\text{Figure 3. Data-to-model ratio plots for 4U 1543−624 illustrating the Fe Kα emission line variability through different epochs.}\)

\(^2\)For more information on pile-up see: http://xmm2.esac.esa.int/docs/documents/CAL-TN-0050-1-0.ps.gz

\(^3\)XMM-Newton CCF Release Note: XMM-CCF-REL-334

\(^4\)http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/
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Figure 4. Normalized counts vs. energy and ratio of the data to the continuum model for the 1997 RXTE observation. The data have been re-binned for clarity; the 3-20 keV energy range is shown.

five Proportional Counter Units (PCUs), with a combined effective area of $\sim 7000\,\text{cm}^2$. Each PCU is composed of three layers of xenon (90%) and methane (10%) composites. Most incident photons with energies below 20 keV are detected in the top layer (layer 1) and for this reason we have opted to only extract spectra from this layer. All PCUs were active during the observation, which allowed us to obtain the data of all detectors for the spectrum extraction. As per the recommendation of the RXTE guest observer facility (GOF), we removed energy channels below 3 keV. Additionally, in our spectral extraction we ignored all channels above 20 keV. The signal-to-noise ratio drops significantly above this threshold, and for this work we are primarily interested in the energy range below 20 keV. Due to the low orbit of RXTE, observations are occasionally affected by the satellite's passage through the South Atlantic Anomaly (SAA) or by Earth occultation of the observed source. Data may also be affected by electron contamination and sporadic breakdowns of the PCU2 detector. For the spectral extraction we filtered out intervals where the elevation angle was less than 10 degrees (to avoid possible Earth occultations) and also any data that may have been received during passage from the SAA. Furthermore, we excluded any data affected by electron contamination, where offset by more than 0.02 degrees or taken 150 seconds before, through 600 seconds after a PCU2 breakdown. Source spectra were extracted and background emission was modeled using standard routines from the FTOOLS package and the latest model for bright sources, provided by the GOF. All spectra where re-binned to a minimum of 30 counts per bin.

The spectral continuum is again modeled with a similar combination of absorbed disk black body and black body emission, and a hydrogen column density ($n_{\text{H}}$) frozen at the Galactic value. The fit yields a reduced $\chi^2$ value of 1.66 for 41 dof, and the data-to-model ratio plot reveals strong positive residuals in the 6-7 keV region (Figure 8). The residual structure – a strong indication of a bright iron Kα emission line – is modeled using a Gaussian. The high energy range of RXTE/PCA (>10 keV) allowed us to also probe the non-thermal tail of the 4U 1543–624 spectrum, which we modeled using power law with a spectral index of $\sim 2.5$ and a high energy exponential cutoff at $\sim 15$ keV. The final fit yields a reduced $\chi^2$ value of 0.44 for 38 dof (Figure 4 for the 3-20 keV best-fit plot). The temperature of the disk black body is $kT_{\text{in}}\sim 0.8$ keV and for the black body is $kT_{\text{BB}}\sim 1.8$ keV. The iron emission line is centered at $\sim 6.58$ keV, has a width of $\sim 670$ eV and an equivalent width (EW) of $\sim 100$ eV. The source luminosity, extrapolated in the 0.50-30 keV range, is $\approx 7.1 \times 10^{36}$ erg/s. All values of the best fit parameters are presented in Table 2.

2.2.3 Chandra December 2000 observation

The Chandra X-ray Observatory has observed 4U 1543–624 four times. One in December of 2000, using the HETG and three more in June 2012 using the Low Energy Transmission Grating (LETG). Below we outline the spectral extraction and analysis for the 2000 HETG observation.

Spectral extraction and analysis.

Using the tools included in the latest version of the CIAO software (vers. 4.8), we extract spectra from both the medium energy grating (MEG) and the high energy grating (HEG). Namely, upon selecting an appropriate extraction region and taking into account the correct source position and telescope orientation during the entire observation, we use CIAO task tmerge to create a standard type II spectral file, containing all spectral orders of both the MEG and HEG detectors, and mktgresp to create their corresponding ancillary files and response matrices. In order to analyze the spectra with XSPEC, we create separate type I PHA files for the MEG and HEG spectra, simultaneously adding the +1 and -1 grating orders and rebinning them to a minimum of 30 counts per bin. We also create a separate background spectrum using the task tbkg.

The spectral continuum is well modeled with the same combination of absorbed disk black body and black body emission, as in the 1997 RXTE and 2001 XMM-Newton observations. The temperature of the disk black body lies at $kT_{\text{in}}\sim 0.65$ keV and the black body temperature at $kT_{\text{BB}}\sim 1.61$ keV. This time, no emission line was detected in the 6-7 keV range and we place a 1 $\sigma$ upper limit for the EW of the iron Kα emission line at 6.13 eV. The double thermal model fit yielded a reduced $\chi^2$ value of 1.02 for 3703 dof. The source luminosity during the Chandra observation, was $\approx 6.1 \times 10^{36}$ erg/s, calculated in the 0.50-30 keV range and assuming a distance of 7 kpc. All values of the best fit parameters are presented in Table 2.

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5 https://heasarc.gsfc.nasa.gov/docs/xte/pea/doc/rmd/pcarmf-11.7/
6 http://heasarc.gsfc.nasa.gov/docs/xte/pcarnews.html
Table 1. List of observations of 4U 1543–624 and Swift J1756.9–2508 analyzed in this paper.

| Instrument          | obsID     | Date         | Duration (ks) |
|---------------------|-----------|--------------|---------------|
| RXTE                | P20071    | 1997-05-06   | 14            |
| Chandra             | 702       | 2000-09-12   | 30            |
| XMM-Newton          | 00611140201 | 2001-02-04   | 50            |
| NICER               | 1050060106 | 2017-08-20   | 13            |
| Swift J1756.9–2508  |           |              |               |

| Instrument          | obsID     | Date         | Duration (ks) |
|---------------------|-----------|--------------|---------------|
| RXTE                | P92050    | 2007-06-16   | 12            |
| XMM-Newton          | 0830190401 | 2018-04-08   | 65            |
| NuSTAR              | 90402313002 | 2018-04-08   | 40            |

1Duration of filtered observations.

2.2.4 NICER Sept. 2018 observation
4U 1543–624 was observed by NICER in 13 separate pointings over a ~10 days starting at August 15 2017. Here we analyse obsID 1050060106, which at a duration of ~13ks, provides the highest number of total counts after the standard event filtering described below.

Spectral extraction and analysis.
The Neutron Star Interior Composition Explorer (NICER; Gendreau et al. 2012) operates on-board the International Space Station and consists of 56 “concentrator” optics and silicon drift detector pairs registering X-ray photons in the 0.2 – 12 keV energy range. The 52 operating collectors comprise a total collecting of $\approx 1900 \text{cm}^2$ at 1.5 keV. NICER-DAS 2018-10-07_V005 was employed for the data reduction process. Namely, using NIMAETIME we created appropriate good time intervals (GTIs), by filtering out all raw data with the standard criteria using various housekeeping parameters (see Bogdanov et al. 2019; Guillot et al. 2019, for more details). The final event list was extracted using NEXTRACT-EVENTS for PI energy channels between 0-1200, inclusive, and EVENT_FLAGS=bxxxx1x000 as per the NICER manual guidelines. For the spectral extraction we used heasoft tool XSELECT. The spectra were subsequently normalized based on the instrumental residuals calibrated from the Crab Nebula, as described in Ludlam et al. (2018).

The background spectrum was generated from a library of NICER observations of “blank sky” fields (the same ones as for RXTE, Jahoda et al. 2006b). Specifically, a weighted-average of these “blank sky” observations with a similar combinations of observing conditions as our target’s data set is used to produce the diffuse cosmic X-ray background spectrum7. The latter is also normalized with the Crab Nebula residual spectrum. Finally, the latest public ARF and RMF files were downloaded from the NICER GOF.

Observed by NICER, almost two decades after the XMM-Newton observations, the spectral continuum of 4U1543–624 is qualitatively the same as in all previous observations and was again modeled with the same combination of absorbed disk black body and black body emission. The accretion disk temperature of the disk black body is closer to its value during the RXTE observation, at $kT_{\text{disk}} \approx 0.80$ keV as is the black body temperature which is estimated at $kT_{\text{bb}} \approx 1.80$ keV. The iron K$\alpha$ emission line has reappeared in the source spectrum, indicated by positive residual structure in the data-to-ratio vs energy plot in Figure 3. The emission line was modeled with a Gaussian centered at $\approx 6.5$ keV, with a width of $\approx 160$ keV and an EW of $\approx 61$ eV. The double thermal model including the Gaussian emission line yielded a reduced $\chi^2$ value of 1.07 for 743 dof. The source luminosity during the NICER observation, was $\approx 6.0 \times 10^{36} \text{ erg/s}$, calculated in the 0.50-30 keV range and assuming the distance of 7 kpc. All values of the best fit parameters are presented in Table 2.

2.3 X-ray spectroscopy of Swift J1756.9–2508
2.3.1 RXTE June 2007 observation
There are two sets of RXTE observations of Swift J1756.9–2508 carried out in 2007 when the source was first detected, and in 2009 during its second outburst. We have reviewed all available data and present here our analysis of the 2007 observation with the higher number of registered counts. For a thorough study of the entire RXTE observation campaign of Swift J1756.9–2508 we refer the reader to the works of Krimm et al. (2007) and Patruno et al. (2010).

Spectral extraction and analysis.
The extraction procedure for the RXTE/PCA spectra of Swift J1756.9–2508 is identical to the one described in paragraph 2.2.2. The X-ray spectrum of Swift J1756.9–2508 during its 2007 outburst is also described by a combination of two absorbed thermal components, which is consistent with the high-luminosity soft-state spectra of weakly absorbed sources.

This background modeling technique is detailed in Bogdanov et al. (2019)
Table 2. Best fit parameters for the XMM-Newton, Chandra, RXTE/PCA and NICER spectra of 4U 1543–624. The errors are 1σ.

| Model parameter | RXTE-PCA 1997* | Chandra 2000 | XMM-Newton 2001 | NICER 2017 |
|-----------------|---------------|-------------|-----------------|------------|
| nH (10^{22} cm^{-2}) | 0.29          | 0.29        | 0.29            | 0.29       |
| **Disk Black Body** |               |             |                 |            |
| kT (keV)        | 0.80^{+0.31}_{-0.22} | 0.71^{+0.004}_{-0.003} | 0.65^{+0.02}_{-0.03} | 0.79^{+0.04}_{-0.03} |
| R_{in} d (km)   | 9.02^{+1.71}_{-1.86} | 12.2^{+6.30}_{-8.26} | 13.6^{+0.74}_{-0.66} | 10.3^{+0.54}_{-0.42} |
| **Black Body**  |               |             |                 |            |
| kT (keV)        | 1.84^{+0.24}_{-0.27} | 1.61^{+0.04}_{-0.03} | 1.53^{+0.05}_{-0.04} | 1.80^{+0.02}_{-0.01} |
| norm e          | 7.48^{+0.34}_{-0.98} | 7.00^{+0.10}_{-0.08} | 9.54^{+0.76}_{-0.76} | 4.26^{+0.15}_{-0.10} |
| **Iron Line**   |               |             |                 |            |
| Centroid E (keV) | 6.58^{+0.21}_{-0.23} | 6.6^{f}       | 6.6^{f}         | 6.47^{+0.12}_{-0.12} |
| Width σ(eV)     | 678^{+133}_{-121} | 500^{f}   | 500^{f}         | 160^{+1.2}_{-1.8} |
| Flux e          | 95.1^{+34.5}_{-23.5} | < 5.05     | < 1.19          | 31.5^{+5.7}_{-5.7} |
| EW (eV)         | 99.3^{+36.6}_{-24.3} | < 6.13    | < 2.68          | 61.3^{+11.7}_{-11.7} |
| L_{total} b     | 6.65^{+0.03}_{-0.07} | 6.14^{+0.09}_{-0.08} | 5.14^{+0.01}_{-0.01} | 5.00^{+0.01}_{-0.01} |
| L_{BBB} c       | 1.56^{+0.46}_{-0.66} | 2.48^{+0.32}_{-1.0} | 2.78^{+0.01}_{-0.01} | 3.35^{+0.18}_{-0.12} |
| L_{BB} c        | 3.82^{+0.64}_{-0.44} | 3.76^{+0.03}_{-0.03} | 2.37^{+0.01}_{-0.01} | 2.54^{+0.09}_{-0.09} |
| L_{BPL} c       | 1.13^{+0.14}_{-0.14} | -          | -               | -          |
| \(\chi^2/dof\)  | 16.9/38        | 3762/3703   | 1858/1795       | 807/743    |

*a* With an additional cutoff power law (\(\Gamma=2.49^{+0.17}_{-0.08}\) and \(E_{cut}=14.8^{+0.85}_{-0.81}\)keV), for the RXTE data.

*b* Parameters frozen at total galactic HI column density provided by the HEASARC nH tool (HI4PI Collaboration et al. 2016).

*c* \(10^{-3}\) ph keV^{-1} cm^{-2} s^{-1}.

*d* Solving K=(1/f_{col})((R_{in}/D)_{10kpc}^{2}) cos i, for R_{in} (the inner radius of the disk in km). K is the normalization of the diskbb model, f_{col} is the spectral hardening factor, D_{10kpc} is distance in units of 10 kpc and i is the inclination.

*e* \((R_{body}/D_{10kpc})^{2}\) where R_{body} is the size of the emitting region in km and D_{10kpc} is distance in units of 10 kpc.

*f* Parameters frozen. The centroid energy value was frozen at the median value of the 6.4-6.9 keV band.

*g* \(\sigma\) is average width of observed Fe Kα emission lines in LMXBs (e.g., Cackett et al. 2009; Ng et al. 2010).

*h* Extrapolated to the 0.50-30 keV range assuming a distance of 7 kpc (Schultz 2003; Wang & Chakrabarty 2004).

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magnetized NS LMXBs (e.g., Lin et al. 2007). As expected for a source in the direction of the Galactic bulge there is considerable interstellar absorption in the line of sight to Swift J1756.9–2508, with nH=6×10^{22} cm^{-2} (HI4PI Collaboration et al. 2016). The accretion disk temperature was estimated at \(kT_{n}\sim1.1\) keV and the temperature of the black body component at \(kT_{BB}\sim2.3\) keV. A prominent iron Kα emission line is clearly detected above the spectral continuum (see Figure 8 for the data-to-model vs energy plot). The emission line is centered at \(\sim6.5\) keV, and has an EW of \(\sim171\) keV. The width of the emission line is smaller than the RXTE/PCA energy resolution (18% at 6 keV) and was thus frozen to 500 eV. In addition to the thermal emission, the fit required a non-thermal component dominating \(\sim10\) keV, which was modelled using a power law with spectral index of \(\sim1\) and a high-energy exponential cutoff at \(\sim12\) keV. The model yields a reduced \(\chi^2\) value of 0.65 for 30 dof. The source luminosity during the RXTE observation, was \(\approx5\times10^{36}\) erg/s, calculated in the 0.50–30 keV range and assuming a distance of 8.5 kpc, based on the source position toward the direction of the Galactic centre. All values of the best fit parameters along with errors in the 1σ confidence range are presented in Table 3.

### 2.3.2 XMM-Newton/NuSTAR April 2018 observation

Swift J1756.9–2508 was jointly observed by XMM-Newton and NuSTAR X-ray telescopes during its third and latest outburst in April of 2018.

*Spectral extraction and analysis.*

During the XMM-Newton observation of Swift J1756.9–2508 the EPIC-pn detector was again oper-
Table 3. Best fit parameters for the combined NuSTAR – XMM-Newton and RXTE/PCA spectra of Swift J1756.9−2508. The errors are 1σ.

| Model parameter | RXTE/PCA | XMM-NuSTAR |
|-----------------|----------|------------|
|                 | 2007     | 2018       |
| nH$^+$. (10$^{22}$ cm$^{-2}$) | 6.05±1.02 | 7.28±0.07 |

Disk Black Body

| kT (keV) | 0.96$_{-0.18}^{+0.39}$ | 1.24$_{-0.06}^{+0.09}$ |
| R$_{in}$ (km) | 3.9$_{-1.04}^{+0.01}$ | 5.45$_{-0.45}^{+0.42}$ |

Black Body

| kT (keV) | 2.27$_{-0.99}^{+0.14}$ | 2.79$_{-0.12}^{+0.17}$ |
| norm$^c$ | 12.3$_{-6.3}^{+5.3}$ | 1.12±0.15 |

Cutoff Power Law

| $\Gamma$ | 0.97$_{-0.25}^{+0.22}$ | 1.39$_{-0.17}^{+0.07}$ |
| norm ($\times$10$^{-3}$) | 11.6$_{-0.27}^{+0.12}$ | 20.1$_{-4.0}^{+9.0}$ |
| $E_{coup}$ (keV) | 11.9$_{-0.69}^{+0.71}$ | 22.8$_{-1.6}^{+1.0}$ |
| $E_{int}$ (keV) | 17.4$_{-2.67}^{+3.41}$ | 50.6$_{-8.2}^{+8.7}$ |

Iron Line

| Centroid E (keV) | 6.47±0.12 | 6.6$^d$ |
| Width $\sigma$(eV) | 500$^d$ | 500$^d$ |
| Flux$^c$ | 42.3±4.5 | < 1.19 |
| EW (eV) | 171±18.5 | < 7.36 |
| $L_{T, total}$(×10$^{36}$ erg/s) | 4.87±0.10 | 3.67±0.02 |
| $L_{BB}$ (×10$^{36}$ erg/s) | 0.84±0.11 | 0.91±0.07 |
| $L_{BB}$ (×10$^{36}$ erg/s) | 1.00±0.12 | 0.67±0.04 |
| $L_{BB}$ (×10$^{36}$ erg/s) | 3.13±0.12 | 2.59±0.25 |
| $\chi^2$/dof | 19.6/30 | 3255/3414 |

$^a$ 10$^{-3}$ ph keV$^{-1}$ cm$^{-2}$ s$^{-1}$.

$^b$ Solving K=(1/4)$f$($R_{in}/D_{10kpc}$)$^2$ cos $i$, for $R_{in}$ (the inner radius of the disk in km). K is the normalization of the diskbb model, $f$ is the spectral hardening factor, $D_{10kpc}$ is distance in units of 10 kpc and $i$ is the inclination.

$^c$ ($R_{body}/D_{10kpc}$)$^2$ where $R_{body}$ is the size of the emitting region in km and $D_{10kpc}$ is distance in units of 10 kpc.

$^d$ Parameters frozen. The centroid energy value was frozen at the median value of the 6.4-6.9 keV range, for a step of 0.1 keV and width value based on average width of observed Fe Kα emission lines in LMXBs (e.g., Cackett et al. 2009; Ng et al. 2010), for the RXTE detection the width is frozen at the instrument’s energy resolution at 6 keV. The two values coincide.

$^e$ 10$^{-5}$ ph cm$^{-2}$ s$^{-1}$.

$^f$ Luminosity extrapolated to the 0.5-30 keV range and assuming a distance of 8.5 kpc, based on the proximity toward the direction of the Galactic centre.

...
We argue that the simplicity and\cite{2015Popham} and\cite{2010Gilfanov} the boundary layer is a transition region between the rapidly spinning accretion disk and the NS which is rotating at slower rate. The optically thick matter that accumulates on the NS surface is predicted to have a temperature of \( \sim 10 \) keV, producing thermal emission that accounts for a significant fraction of the total accretion luminosity.

The most notable narrow emission feature detected on top of the spectral continuum (in the energy range \( \gtrsim 10 \) keV) was a prominent and broad Fe K\alpha emission line, centered at \( \approx 6.5 – 6.6 \) keV. The iron emission line is observed in both sources during two different instances and in the case of 4U 1543–624 by two different instruments. In general, the presence of iron emission is a common characteristic in the X-ray spectra of accreting compact objects and is the result of "reflection" of X-rays from the surface of the accretion disk (e.g., see\cite{2007Done};\cite{2010Gilfanov}, and references therein). Namely, hard X-rays are reflected off the accretion disk, and the reflected component is registered along with the primary disk emission. The Fe K\alpha line is the result of this reflection, as a fraction of high energy photons – that are "absorbed" by iron atoms – are remitted at the energy corresponding to the electron transition from the 2p orbital of the L-shell to the innermost K-shell. While the detection of iron fluorescence in X-ray spectra of LMXBs – such as 4U 1543–624 and Swift J1756.9–2508 – is a frequent and expected occurrence, a much more extraordinary event, is the fact that the emission line seems to have disappeared during some of the available observations.

3 DISCUSSION

We have analyzed the spectra of 4U 1543–624 and Swift J1756.9–2508 during different periods in their observational history. In all observations the sources appeared to have been captured in an accretion dominated (soft) state. In this state the accretion disk is extending close to the compact object (in our case a NS) and the observed spectrum is dominated by thermal emission. We have modeled the spectra of both sources using a combination of a multicolor disk black body and a black body model with very high temperature (with the addition of a non-thermal tail when required). The choice for this model is motivated by the well established theoretical framework for accretion onto low-B NSs and the formation of a hot optically thick layer of material on the NS surface, known as the boundary layer (e.g.,\cite{1986SunyaevShakura};\cite{2001PophamSunyaev};\cite{2003Gilfanov} et al.). The boundary layer is a transition region between the rapidly spinning accretion disk and the NS which is rotating at slower rate. The optically thick matter that accumulates on the NS surface is predicted to have a temperature of \( > 1 \) keV, producing thermal emission that

Figure 8. Data-to-model ratio plots for the two sources with a variable Fe K\alpha emission line.

3.1 Fe K\alpha line variability and the spectral state of the two UCXBs

The spectral continuum of 4U 1543–624 displays a remarkable consistency throughout all available observations, which have been carried out over two decades. Within our interpretation for the origin of the emission in 4U 1543–624, the bulk of the 0.5–10 keV emission appears to be produced by an accretion disk with a temperature of \( \sim 0.6–0.8 \) keV and an inner disk radius of the order of 10 km and an additional, hot thermal source with a \( \sim 1.5 – 1.8 \) keV temperature. The luminosity of the source has varied moderately by a factor of up to 25%, and any minor variability of its spectrum is mostly manifested in the relative flux of each spectral component. Over the course of its observational history, the spectrum of 4U 1543–624 has been modelled using a variety of different models, including black body, disk black body models, power-law components with high energy cutoffs below 10 keV, as well as broken power-laws with two spectral indexes, or more complex X-ray reflection models (e.g.,\cite{2003Schultz};\cite{2003Farinelli} et al.;\cite{2011Madej};\cite{2014Madej}). We argue that the simplicity and long term consistency of our chosen model, combined with the fact that it yields physically realistic estimations of key emission parameters (see below), favors our interpretation for the origin of the source emission. During the 1997 RXTE observation we detected a Fe K\alpha emission line with an EW of \( \sim 100 \) eV, which is not present in either the Chandra or XMM-Newton spectra with a stringent EW upper limit of 6.13 eV and 2.86 eV, respectively. The line is detected again in the 2017 NICER observation with an EW of \( \sim 60 \) eV.

For Swift J1756.9–2508, we consider the same interpretation for the origin of the spectral continuum as for 4U 1543–624. This source also appears to have a stable
spectral shape during its three recorded outbursts (in this work we present the 1st and 3rd outburst, for the 2nd outburst see Patruno et al. 2010). However, we do note the detection of minor, but non-negligible differences in the temperatures of the thermal components ($kT_{\text{in}} \sim 0.96$ keV in RXTE vs $kT_{\text{in}} \sim 1.24$ keV in the XMM-Newton/NuSTAR data and $2.3$ keV vs $2.8$ keV for the thermal emission) and a moderate variability (order of $\times 7$) in the relative flux of the hot thermal component between observations. Nevertheless, as in the case of 4U 1543–624, the most striking difference between the Swift J1756.9–2508 spectrum of 2018 and the one of 2007 is the disappearance of the prominent Fe Kα line. Namely, the bright iron emission line detected in the 2007 RXTE observation with an EW of $\sim 170$ eV, is not detected during the 2018 XMM-Newton/NuSTAR observation with an EW upper limit of $7.36$ eV. We also note a 25% variation of the total source flux.

A Crucial factor for establishing the reliability of our interpretation of the spectral continuum in both sources – and more importantly for identifying the cause for the notable variability of the strength of the iron emission line – is the rigorous estimation of true values of its spectral parameters. i.e., the temperature and inner radius of the accretion disk. To further assess the plausibility of our best-fit estimations, it is also important to compare our findings with theoretical expectations. In two of the Swift J1756.9–2508 observations (RXTE and NICER), the best value of the inner disk radius is measured in the $\sim 8$-10.5 km range, while for Swift J1756.9–2508 they range between $\sim 4$ and $\sim 6$km. These estimations lie below the value of the NS radius which is $\sim 9$-15 km depending on the equation of state of the NS (e.g., Özel & Freire 2016, and references therein), and therefore appear to be unrealistically small. Nevertheless, we note that in all tabulated values we have not considered the necessary corrections of the thermal component parameters due the spectral hardening expected from the high plasma temperature. Correcting the inner radius estimations, assuming a moderate value of 1.8 for the spectral hardening factor (see Section 2.1), yields $R_{\text{in}}$ values in the $\sim 15 - 45$ km for the entire set of observations, which is the typical size for an accreting low-B NS in the soft state.

Therefore within this framework, the presence of iron Kα fluorescence in the spectra of 4U 1543–624 and Swift J1756.9–2508 is the result of illumination of the inner accretion disk by the boundary layer emission. Since the iron line is produced by X-ray reflection, its shape and strength are highly sensitive to the geometrical arrangement between the source of the primary emission (e.g., the boundary layer) and the accretion disk. Modification of the size and temperature of the emitting region, the inner radius of the accretion disk and the direction of the hard X-ray emission, will affect the size and location of the illuminated region of the disk. These effects will become especially pronounced in case of spectral state transition towards the so called “hard” state of accretion, were the disk recedes from the central source, giving way to the formation of an extended region of advection-dominated, optically thin radial flow. This “corona” consisting of very hot electrons produces copious amounts of non-thermal photons, resulting in a spectrum that is dominated by the power-law shaped component. Therefore, state transitions can have profound effects on the strength of the iron emission line (e.g., Ng et al. 2010; Cackett et al. 2010; Kolehmainen et al. 2014). Similar effects can also be observed in accreting highly magnetized NS (i.e., high-B, X-ray pulsars), where variations in the accretion rate affect the size of the magnetosphere, the inner disk radius and the direction of the pulsar beam, resulting in pronounced variability in the iron line strength (e.g., Koliopanos & Gilfanov 2016). Therefore the striking variability of the iron line as observed in 4U 1543–624 and Swift J1756.9–2508 are expected to occur in tandem with major modification of the spectral continuum and/or the source luminosity.

However, one of the main findings of our analysis, is the notable stability of the spectrum and luminosity of both sources throughout the different observations with or without the presence of iron Kα fluorescence. This suggests that the attenuation of the iron line is not caused by a “macroscopic” transition in the accretion state of the source, but is likely the result of a more subtle microscopic process. To our knowledge such remarkable emission line variability in an otherwise stable X-ray binary has not been previously observed. However, the possibility of this phenomenon had been hypothesized by Koliopanos et al. (2013) for UCXBs with C/O-rich donors.

### 3.2 Variability of the Fe Kα line in UCXBs with C/O-rich donors

In Koliopanos et al. (2013), it was demonstrated that the Fe Kα emission line in the spectra of UCXBs with C/O-rich donors, is expected to be strongly attenuated, with expected values of the EW to be less than $10$ eV. The attenuation of the iron emission line is primarily due to the presence of overabundant oxygen in the accreting material. Namely, contrary to accretion disks with solar-like abundance, in the C/O-rich disks, absorption of photons with energies equal to or higher than the ionization threshold of iron ($E_{\text{ion}} \approx 7.1$ keV), is dominated by oxygen rather than by iron. This results in the strengthening of the oxygen emission line (centered at $\sim 0.68$ keV) and the strong attenuation of the iron line. More specifically, after running the MCMC code of Koliopanos et al. (2013) for an incident 1 keV black body spectrum and for a range of observer viewing angles between $10^\circ$ and $50^\circ$, we find that an $O/Fe$ ratio of at least 50 times the solar value, is required to explain the absence of a Fe Kα line at an EW upper limit of 8 eV. This screening effect, will hold, as long as the oxygen in the accretion disk is not fully ionized.

The ionization state of elements in the disk was not self-consistently treated in the model developed by Koliopanos et al. (2013). However, the effects of the ionization state of the disk were discussed – under a set of spe-

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8 The maximum value of the O/Fe ratio corresponding to the chemical composition of a C/O white dwarf – in which all hydrogen and helium has been converted to carbon and oxygen – is $\approx 77$ times the solar value.
cific assumptions. Namely, we considered that the ionization state of the disk is determined solely by heating due to viscous dissipation as illustrated in the Shakura & Sunyaev (1973) formulation. We have ignored the effects of disk irradiation by assuming the conditions described in the Nayakshin et al. (2000) analysis, predicting the formation of a thin, fully ionized layer on the disk surface which is dominated by X-ray illumination, while the temperature of deeper disk layers remain unaffected. Within this regime, Koliopanos et al. (2013) roughly estimated that during the soft state and for a mass accretion rate \( (M) \) corresponding to \( L_X \) of the order of a few \( \times 10^{37} \text{erg/s} \), oxygen could become fully ionized in the accretion disk of an UCXB, thus canceling its screening effect on the iron line. Within this framework the iron line variability in UCXBs is luminosity dependent.

More specifically assuming an optically thin, geometrically thin disk following the Shakura-Sunyaev \( \alpha \)-disk model, the effective temperature of the disk is given by

\[
T_{\text{eff}} = \left( \frac{3GM}{8\pi\sigma r_0^3} \right)^{1/4} \left( \frac{r_o}{r} \right)^{3/4} \left( 1 - \sqrt{r_o/r} \right)^{1/4}
\]

where \( \sigma = 5.67 \times 10^{-5} \text{erg cm}^{-2} \text{s}^{-1} \text{K}^{-4} \) is the Stefan-Boltzmann constant, \( M \) is the mass of the accretor (~ 1.4 \( M_\odot \) for a neutron star), \( r_0 \) the mass accretion rate and \( r_0 \) is the inner radius of the disk, which in the case of the soft state of a neutron star is close to its radius. For a moderate \( M \), (corresponding to \( L \approx 2 \times 10^{37} \text{erg/s} \)), the temperature of the inner parts of the disk (up to 15 \( R_\odot \)) will range between 5-8 \( \times 10^6 \text{K} \). In addition to heating due to viscous dissipation, if the accretion disk forms a boundary layer near the surface of the NS, it will cause a dissipation of the kinetic energy of the inner disk rings, which in turn will result in the inflation and heating of the innermost part of the disk. Inogamov & Sunyaev (1999) calculate that the inner disk will be heated to \( \sim 10^7 \text{K} \) as the boundary layer forms. When the temperature reaches \( \sim 10^7 \text{K} \) – and assuming that the disk plasma is in collisional ionization equilibrium, in a coronal approximation – 90%-100% of oxygen will be fully ionized (Shull & van Steenberg 1982).

The above analytical estimations demonstrate, that for typical conditions that can be met by moderately bright UCXBs, it is very likely that a considerable fraction of the inner accretion disk can reach a high enough temperature for all oxygen to become fully ionized. Although there is considerable uncertainty in the distance estimation for our two sources – different estimations place 4U 1543 – 624 anywhere between 1.4-11.5 kpc (Serino et al. 2018; Bailier-Jones et al. 2018), while Swift J1756.9 – 2508 is assumed to be at a distance of 8.5 kpc due to its proximity to the galactic bulge, we can robustly place both sources in the in the \( 10^{36} - 10^{37} \text{erg/s} \) range. From our analysis, the color-corrected, maximum disk temperature obtained by the \texttt{diskbb} model, during the epochs when the line is detected is \( \sim 5 \times 10^{6} \text{K} \) for 4U 1543 – 624 and \( \sim 8 \times 10^{6} \text{K} \) for Swift J1756.9 – 2508 (we note that \texttt{diskbb} is only an approximation of the full Shakura & Sunyaev (1973) treatment).

The X-ray luminosity of both sources is marginally lower than the rough threshold of \( \log(L_X) \sim 37.5 \) suggested by Koliopanos et al. (2013). Similarly the spectroscopic estimations of the accretion disk lies below the \( \sim 1 \text{KeV} \) value for the full ionization of 100% of the disk oxygen, but only marginally so. If we also take into account that the state-of-the-art Monte-Carlo simulations of X-ray reflection (e.g., Garcia & Kallman 2010; Garcia et al. 2011; Garcia et al. 2013) indicate that X-ray irradiation can increase the disk ionization at deeper layers than the Nayakshin et al. (2000) estimations, we can reasonable assume that our sources lie exactly at the threshold between having most of their oxygen partially ionized (suppression of Fe Kα line) to fully ionized (re-appearance of Fe Kα line). We note that in both cases the overabundance of oxygen expected in the C/O-rich disk (50-80 times the Solar value) ensures the presence of notable \( O_{\text{VIII}} \) fluorescent line even when most of it becomes fully ionized (although the actual detection of such a feature depends on multiple additional parameters; see discussion in Koliopanos et al. 2013). Indeed this line is detected at \( \sim 0.68\text{keV} \) in 4U 1543 – 624, where the low absorption allows for its detection (see Figure 1 and refer to Ludlam et al. 2019 for an analysis of the NICER observation).

We argue that the disappearance of the iron line occurring within an otherwise non-variable spectral state, is a strong indication that 4U 1543 – 624 and Swift J1756.9 – 2508 are both C/O-rich UCXBs observed at the threshold at which the screening of the iron line ceases to exist. As a result of this precarious state, subtle variations on the parameters of the accretion process, may lead to increase in the fraction of fully ionized oxygen, evidenced by the reappearance of the iron emission line. Besides this striking variability in the Fe Kα line flux, the change in the ionization state has negligible effects on other observables. We consider this discovery an encouraging result with respect to the Koliopanos et al. (2013) theoretical predictions on X-ray reflection off H-poor disks in UCXBs and their potential use as a diagnostic of the composition of the accretion disk and donor star in these sources.

### 4 SUMMARY AND CONCLUSIONS

We have analyzed multiple observations of known UCXBs 4U 1543 – 624 and Swift J1756.9 – 2508, carried out over a different eras within a 10-20 year period and by different instruments. We have demonstrated that both sources (one is a persistent and the other a transient source), exhibit a remarkable stability on the shape of their spectral emission and their X-ray luminosity (during outburst). Nevertheless, we also detected a pronounced difference in the spectral characteristics at different epochs, in the form of a striking variability in the strength of the iron Kα emission line. Namely, the emission line either detected as a prominent feature with an EW of 100-170 eV, or completely disappears with an EW upper limit of less than 8 eV. Based on the stability of the spectral shape and flux of both sources throughout the different observations, and on the values of their spectral parameters, we have attributed the iron line variability to a change in the ionization state of oxygen in the inner accretion disk regions. Namely, subtle variations of
the accretion disk parameters can lead to a transition from partially to fully ionized oxygen in the disk, which in turn affects the strength of the iron line, as has been predicted for UCXBs with C/O-rich donors by Koliopanos et al. (2013). We argue that this behavior supports the theoretical arguments of this work and favors the C/O-rich classification of the UCXBs 4U 1543–624 and Swift J1756.9–2508.

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