The chemical composition of the accretion disk and donor star in Ultra Compact X-ray Binaries: A comprehensive X-ray analysis

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ABSTRACT
We have analyzed the X-ray spectra of all known Ultra Compact X-ray Binaries (UCXBs), with the purpose of constraining the chemical composition of their accretion disk and donor star. Our investigation was focused on the presence (or absence) of the Fe K\textalpha emission line, which was used as the probe of chemical composition of the disk, based on previously established theoretical predictions for the reflection of X-ray radiation off the surface of C/O-rich or He-rich accretion disks in UCXBs. We have contrasted the results of our spectral analysis to the history of type I X-ray bursts from these systems, which can also indicate donor star composition. We found that UCXBs with prominent and persistent iron K\textalpha emission also featured repeat bursting activity. On the other hand, the UCXBs for which no iron line was detected, appear to have few or no type I X-ray bursts detected over more than a decade of monitoring. Based on Monte Carlo simulations, demonstrating a strong correlation between the Fe K\textalpha line strength and the abundance of C and O in the accretion disk material and given the expected correlation between the H/He abundance and the recurrence rate of type I X-ray bursts, we propose that there is a considerable likelihood that UCXBs with persistent iron emission have He-rich donors, while those that do not, likely have C/O or O/Ne/Mg-rich donors. Our results strongly advocate for the development of more sophisticated simulations of X-ray reflection from hydrogen-poor accretion disks.

Key words: keyword1 – keyword2 – keyword3

1 INTRODUCTION

Ultracompact X-ray binaries (UCXBs) are X-ray binary systems (XRBs) defined by their extremely short orbital periods of less than \textasciitilde one hour. The orbital size defined by such short periods is too small to encompass the main sequence or red giant stars that make up for the donor star in typical low-mass XRBs (LMXBS), (e.g. Rappaport & Joss 1984; Nelson, Rappaport & Joss 1986b). UCXBs consist of a neutron star (although black holes have not been ruled out), that is accreting matter from degenerate companion star, a Roche-lobe filling white dwarf or helium star (e.g. Tutukov & Yungelson 1993; Iben, Tutukov & Yungelson 1995; Verbunt & van den Heuvel 1995; Deloye & Bildsten 2003; Deloye, Bildsten & Nelemans 2005).

UCXB formation history can be divided into three major schemes. White dwarf (WD) neutron star (NS) binaries that gradually loses angular momentum due to gravitational radiation until the WD fills its Roche lobe and starts losing mass to the NS Pringle & Webbink (1975). Semi-attached binaries reaching an exceptionally short orbital periods, resulting in high mass accretion rates from hydrogen-depleted non-degenerate donors Nelson et al. (1986a) or – in case of a companion star with a helium burning core at the time of contact – a helium star donor Savonije et al. (1986). Therefore, depending on the evolutionary track that leads to their creation UCXBs can have a variety of different donors ranging from Helium stars to C/O or O/Ne/Mg WDs (e.g. Savonije, de Kool & van den Heuvel 1986; Poelsadlowski, Rappaport & Pfahl 2002; Yungelson, Nelemans & van den Heuvel 2002; Bildsten & Deloye 2004).

UCXBs offer the unique opportunity to study accretion of matter with extraordinary chemical composition. Furthermore, they are unique laboratories for the study of binary evolution theory and particularly the common-envelope phase and its relevance to type Ia supernovae and are strong GR wave sources in the low-frequency regime where the ESA/NASA LISA will be sensitive (e.g., Nelemans & Jonker 2010; Amaro-Seoane et al. 2017; Cornish & Robinson 2017). They stand as excellent candidates for in-depth multi-messenger studies of accretion onto compact sources. As population studies and disk stability and evolution analyses predict specific ratios of He-rich vs C/O - O/Ne/Mg systems, a key step in understanding of UCXB formation and evolution is the determination

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of the nature of the donor star composition and whether it lies in the one or the other category (Belczynski & Taam 2004; Nelemans et al. 2010; Heinke et al. 2013).

The most straightforward approach to the determination of donor star composition would be the spectral analysis of optical emission originating in the accretion disk and donor star. Indeed, for a fraction of UCXBs indications of extra-solar elemental abundances have been presented using optical and UV spectroscopy. Nelemans et al. (2004); Werner et al. (2006) and Nelemans et al. (2006) detected strong C and O lines in the optical spectra of two UCXBs (4U 1626-67, 4U 0614+09) which also lacked any evidence for the presence of H or He, suggesting the two source may host C/O rich donors. Furthermore, Nelemans et al. (2006) argued that 4U 1543-624 & 2S 0918-549 show optical spectra similar to 4U 0614+09. On the other hand, a He/N ratio consistent with a He-rich donor was indicated for 4U 1916-05 (Nelemans et al. 2006). While optical spectroscopy can provide good indications for the chemical composition of UCXB donor stars, due to their small sized accretion spectroscopy can provide good indications for the chemical composition of UCXB donor stars, due to their small sized accretion disks (van Paradijs & McClintock 1994) the optical emission from UCXBs is quite faint, with V-band absolute magnitudes typically larger than $>5$ and for distances ranging from $≈3$-12 kpc (e.g. Nelemans et al. 2004, 2006). Therefore, establishing definitive evidence of the donor star composition – using optical spectroscopy – is a challenging task that can only be attempted using the latest generation of $>8$ m telescopes.

As their name implies UCXBs are powerful sources of X-ray emission, the result of mass accretion at high mass accretion rates due to Roche lobe overflow of the donor star (see review by Nelemans & Jonker 2010). Furthermore, the rate and stability of mass accretion depends strongly on the donor star mass and chemical composition and therefore on the evolutionary track that for UCXB formation (e.g. Heinke et al. 2013, and references therein). This paper is focused on the X-ray emission of UCXBs and demonstrates how X-ray spectroscopy, combined with numerical simulations of fundamental radiative processes, in the accretion disk and its vicinity can provide credible indications on the chemical composition of the accretion disks and donor stars of UCXB systems. In Section 2 we lay out the main principles of X-ray diagnostics of the chemical composition of UCXBs, followed by Section 3, where we present the results of X-ray spectroscopic analysis of all known UCXBs. We discuss our findings and present our conclusions in Sections 4 and 5.

2 X-RAY DIAGNOSTICS OF UCXBs

The primary X-ray emission originates in the inner accretion disk and/or the surface layer hot optically thick matter on the NS, known as the boundary layer (Popham & Sunyaev 2001). A secondary emission – evident by the hard X-ray emission with a non-thermal spectrum – originates in a corona of hot thermal electrons in the vicinity of the disk and central engine. The hot electrons up-scatter seed photons from the disk and boundary layer, producing emission with a spectrum characteristic of unsaturated thermal comptonization (e.g. Gilfanov 2010, and references therein). A fraction of these hard photons may be "reflected" (partially absorbed and re-emitted and/or scattered) off the accretion disk surface producing an additional emission component known as X-ray reflection (Basko et al. 1974; White et al. 1988; Lightman & White 1988; George & Fabian 1991).

X-ray reflection spectra are enriched with multiple emission lines – the result of K-shell emission from heavy elements present in the accreting material. However, most of the line photons are heavily diluted by the primary continuum photons (registered together with the reflected emission). Due to the high fluorescence yield and chemical abundance of iron, a bright Fe K α emission line at $≈ 6.4–6.9$ keV with an equivalent width (EW) typically of the order of $≈ 100$ eV (e.g. Cackett et al. 2010) is usually detected in the spectra of normal LMXBs with main sequence or red giant donors. Spectral analysis of the reflection component – and particularly Fe Kα line – can provide indications for the disk chemical composition and its physical parameters such as temperature and rotational velocity and size (e.g. Fabian et al. 1989; Matt et al. 1993, 1997; Ballantyne et al. 2001; García & Kallman 2010; García et al. 2013; Koliopanos et al. 2013).

In the case of UCXBs, X-ray reflection can – in principle – provide valuable insight into the abundances of chemical elements in the disk and donor star, thus revealing its nature. More specifically, the presence of O and Ne emission features – that appear in the spectra of reprocessed emission from the accretion disk and white dwarf surface – (e.g. Madej et al. 2010) and K-edges stemming from absorbing material in the vicinity of the disk (e.g. Schulz et al. 2010) could provide direct indication of a C/O or O/Ne-rich disk and donor star. However, due to increased interstellar absorption below 1 keV and contamination of the reflected component by the primary emission, detection of these features with sufficient accuracy, often proves to be difficult.

In Koliopanos et al. (2013) we used the Monte Carlo method to develop – for the first time – simulations of reflection from C/O or O/Ne/Mg, hydrogen poor disks (Koliopanos et al. 2013). Our study demonstrated that the most striking effect of the hydrogen poor, C/O rich material is not an appearance of strong fluorescent lines of carbon and oxygen – as one might expect – but nearly complete disappearance of iron Kα line located at 6.4 keV. More specifically, for a source of moderate luminosity ($L_X ≲ a few 10^{35}$ erg s$^{-1}$) we predicted a strong suppression of the Fe Kα line in the case of a C/O or O/Ne/Mg WD donor. This translates to a more than an order of magnitude decrease of the EW of the line. On the other hand, in the case of a He-rich donor the iron line is expected to remain unaffected. These predictions were observationally tested in Koliopanos et al. (2014) where we demonstrated that this effect can be used as a diagnostic of the chemical composition of the accretion disk and donor star of UCXBs.

In addition to the direct approach of spectral analysis, the composition of the accreted matter can be indirectly inferred by monitoring the systems’ bursting activity in NS powered UCXBs (all known UCXBs host NSs). Type I X-ray bursts are the result of accumulation of H and/or He on the NS surface until it reaches the necessary conditions to ignite as a thermonuclear flash (e.g. Grindlay et al. 1976; Hansen & van Horn 1975 and for a detailed review Strohmayer & Bildsten 2006). Based on their recurrence rate and temporal characteristic (duration, lightcurve) one can indicate the donor type chemical composition in UCXBs, from their bursting activity. However, it must be noted that the persistence and the rate of the accretion process are also crucial factors determining the bursting activity of X-ray binaries.

In this paper we build on the predictions of Koliopanos et al. (2013) and the findings of Koliopanos et al. (2014) in order to provide an assessment of the donor star type of all known UCXBs. We study X-ray spectra from various X-ray observatories for all known UCXBs and use our simulations to estimate the chemical composition of disk and donors star, based on the presence and strength of the iron Kα line. We evaluate our results by comparing with previous considerations, based on available optical analysis. We further
account for the bursting activity of each source – based on the latest available monitoring information – contrasting their activity to our own estimations in order to scrutinize our classification. Our aim is to use X-ray spectroscopy to diagnose the chemical composition of the donor star of UCXBs, and provide a substantial addition to the study of the evolution of double degenerate systems.

3 DATA SELECTION, EXTRACTION & ANALYSIS

We analyse all confirmed UCXBs (i.e. with a measured optical period of less than 1 h). There are 15 such source known. We primarily use XMM-Newton observations since they provide the optimum combination of spectral resolution and effective area, in the 6-7 keV, to allow for clear line detection and EW estimation but more importantly to attain a tight upper limit in sources were no line is detected. For this reason we selected observations at high count rate. In case were XMM-Newton data were unavailable we made use of NuSTAR or RXTE observations. For all UCXBs we report their bursting activity (or lack there of), based on the archive all high energy all-sky monitors, such as the All Sky Monitor (ASM, on board RXTE), BeppoSAX, JEM-X (on board INTEGRAL), Fermi-LAT and MAXI. We reference the works of Jenke et al. (2016) and (Cumming 2003, for 4U 1820-30), Degenaar et al. (2013); Keek et al. (2017) and Strohmayer et al. (2018) for IGR J17062-6143, (Cumming 2003, for 4U 1820-30), Degenaar et al. (2013); Keek et al. (2017) and Strohmayer et al. (2018) for IGR J17062-6143, the Multi-Instrument Burst Archive (MINBAR) and the SRON catalog of X-ray bursters in ‘t Zand et al.). In Table 1 we present the list of sources analysed in this work, the ObsIDs of the selected observations along with their distances and count rates.

3.1 XMM-Newton spectral extraction

For the XMM-Newton data, we only considered the EPIC-pn detector. EPIC-pn has the largest effective area of the three CCD detectors on board the XMM-Newton (approximately five times higher than that of MOS detectors at ~7 keV). Furthermore, all sources have very high count-rates registering ≥5×10^7 photons for each of the observations considered, thus providing sufficient statistics to robustly detect the presence of emission lines – or place tight EW upper limits when not detected. Using one type of detector ensures simplicity and self-consistency in our analysis. Therefore the following description of data analysis refers only to the EPIC-pn instrument.

The data were handled using the XMM-Newton data analysis software SAS version 18.0.0. and the calibration files released on January 22, 2016[put new date]. Following the standard XMM-Newton guidelines, we filtered all observations for high background-flaring activity, by extracting high-energy light curves (10<E<12 keV) with a 100 s bin size. By placing appropriate threshold count rates for the high-energy photons, we filtered out time intervals that were affected by high particle background.

With the exception of 4U 0513-40 (ObsID:0151750101) and 4U 1850-087 (ObsID:0142330201), which were taken in full window Imaging mode, all other XMM-Newton observations had pn operating in Timing Mode. In this mode, photon coordinates are resolved only in one dimension, along the column axis, greatly increasing the CCD read out speed. In addition to the resulting high temporal resolution, the timing mode is especially appropriate for bright source observations, since it allows for source with higher count rates to be observed without being affected by pile-up. Pile-up effect occurs when, due to a high incident flux, two or more photons hit the detector at approximately the same location and within a smaller time interval than the readout time. As a result the photons are registered as one single photon with a higher energy than the original two photons, resulting in - among others - the artificial hardening of the spectral continuum. Therefore, for high count-rate sources, it is preferable to use data collected in timing mode with a time resolution of 0.03 ms than data collected in large window mode, 48 ms, or in full frame mode, 73 ms. Nevertheless, for bright enough sources pile-up can occur even in the timing mode of EPIC-pn. All XMM-Newton observations were evaluated for source piled-up, by applying the SAS task epatplot on the event list. The task traces the observed pattern distribution compared to the expected distribution in an additional file. Pile-up is indicated by deviations from the model in which case spectral fit results are expected to be erroneous. All XMM-Newton observations considered for this work have been checked and for pile-up and were found to be unaffected (whether in Imaging or Timing mode). Only in the case of 4U 1820-30, all available XMM-Newton observations suffered from pile-up, for this reason a recent NuSTAR observation was used for our analysis.

For the two sources observed in Imaging mode, spectra were extracted from a circular region with a radius 45° centered at the core of the point spread function (psf) of each source. We thus ensured the maximum encircled energy fraction in the extraction region. The extraction and filtering process followed the nominal guidelines provided by the XMM-Newton Science Operations Centre (SOC). Spectral extraction was done with SAS task evselect using the standard filtering flags (#XMMEA_EP && PATTERN<=4 for pn), and SAS tasks rmfgen and arfgen were used to create the redistribution matrix and ancillary file, respectively. The spectra were regrouped to have at least 25 counts per bin and analysis in order to allow for the use if χ^2 statistics in the spectral fitting. Source photons for all pn observations, taken in timing mode, were extracted from the RAW coordinate event file. More specifically the source spectra where extracted from 12 columns comprising the core source emission located between RAWX 25 and 50 for 4U 1820-30, all available XMM-Newton observations suffered from pile-up, for this reason a recent NuSTAR observation was used for our analysis.

3.2 NuSTAR spectral extraction

For the analysis of the NuSTAR data, we used version 1.8.0 of the NuSTAR data analysis system (NuSTARDAS) and instrumental calibration files from CalDB v20180312. We used the IOPIPELINE script to calibrate and clean the data, considering the standard settings reference in the NuSTAR observer’s manual. We reduced internal high-energy background, and screened out all passages through the South Atlantic Anomaly (settings SAACALC=3, TENTACLE=NO and SAA_MODE=OPTIMIZED). Source and background spectra were extracted using the EPIC products routine and instrumental responses were then produced for each of the two focal plane CCD detectors (FPMA/B). The source spectrum was

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1. [http://burst.sci.monash.edu/wiki/index.php?n=MINBAR.V99ReleaseNotes](http://burst.sci.monash.edu/wiki/index.php?n=MINBAR.V99ReleaseNotes)
2. [https://personal.sron.nl/~jeanz/bursterlist.html](https://personal.sron.nl/~jeanz/bursterlist.html)
3. XMM-Newton CCF Release Note: XMM-CCF-REL-332
4. See XMM-Newton Users Handbook §3.2.1.1 [http://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/onaxisixraypsf.html](http://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/onaxisixraypsf.html)
5. [http://www.cosmos.esa.int/web/xmm-newton/sas-threads](http://www.cosmos.esa.int/web/xmm-newton/sas-threads)
extracted from a circular region of 50\' radius, and the background was estimated from a region of the same size, in a blank sky region on the same detector as the source, so far from the source as possible in order to avoid contribution from the PSF wings. Standard PSF, alignment and vignetting corrections were applied upon extraction.

3.3 RXTE spectral analysis

We used data from the RXTE mission for sources XTE J0929-314, Swift J1756.9-2508 and NGC 6440 X-2, for which no high quality data were available from other observatories. More specifically we obtained and analyzed spectra from the Proportional Counter Array (PCA, Jahoda et al. 2006) instrument on board RXTE. From the three on-board instruments – the All Sky Monitor Monitor (Levine et al. 1996), the PCA and the High Energy X-ray Timing Experiment (HEXTE Rothschild et al. 1998) – the PCA has the highest energy resolution (18% at 6 keV), in the spectral range of interest (5–7 keV). While PCA lacks the energy resolution of the CCD detectors on board XMM-Newton and NuSTAR it has a very high effective area, yields spectra with very high S/N ratio and is ideal for emission line-detection (and EW estimation), even if it cannot provide extremely accurate centroid energy or line-width estimation.

The PCA detector consists of five Proportional Counter Units (PCUs), with a combined effective area of ~7000 cm$^2$. Each PCU is composed of three layers of xenon (90%) and methane (10%) composites. The Incident photons with energies exceeding 20 keV are mostly detected in the top layer (layer 1). We, therefore consider only spectra from this layer. Following the guidelines\textsuperscript{6} from the RXTE guest observer facility (GOF), we ignore energy channels below 3 keV recommendation. We also removed all channels above 30 keV. Signal-to-noise ratio drops significantly above ~20 keV, and for this work we are only interested in the energy range below 20 keV.

We filtered out observation 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 through the South Atlantic Anomaly. Furthermore, we excluded any data affected by electron contamination, were offset by more than 0.02 degrees or taken 150 seconds before, through 600 seconds after any observation. 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\textsuperscript{7}.

3.4 Spectral analysis

The X-ray spectral analysis was performed using the Xspec spectral fitting package, version 12.9.0 (Arnaud 1996). For the continuum fitting we used simple models consisting of the fewest possible free parameters. These were the Xspec model diskbb for a multicolor disk black body (MCD), the spherical black body model (bbodyrad) for thermal emission components and a simple power-law model (with occasional exponential cutoff) for non-thermal emission. Despite their simplicity, all models are physically motivated. The MCD component is expected to originate in the accretion disk and the power law simulates non-thermal emission from a hot electron corona (e.g., Done et al. 2007; Gilfanov 2010). The additional bbodyrad component was employed to model thermal emission from the NS surface, known as boundary layer emission (e.g. Popham & Sunyaev 2001).

When detected, the Fe Kα emission line is modeled using a simple gaussian model, based on which we estimate the EW. For

\textsuperscript{6} https://heasarc.gsfc.nasa.gov/docs/xte/pcamf/pcarmf-11.7/

\textsuperscript{7} http://heasarc.gsfc.nasa.gov/docs/xte/pca_news.html
consistency check, we estimated the EW of the emission line in the observed spectra. In most cases, dedicated analysis of these features has been done by previous authors. We refer to these works in all relevant segments of our text.

3.5 Source specific comments

Below we briefly describe the spectral analysis of each source in the UCXB catalog. When thermal emission is detected we convert the model normalization parameter into inner disk radius (for the diskbb model) and size of emitting region (for the bbodyrad model). These estimations depend on the source distance – and the error bar estimation is dominated by the distance estimation. All current distance estimations are presented in Table 1. The interstellar absorption was modeled using the improved version of the tbabs code\(^8\) (Wilms et al. 2000). The atomic cross-sections were adopted from Verner et al. (1996). All best-fit values for the continuum fitting are presented in Table 2. All estimations for the iron Kα emission line are tabulated in Table 3. In this table we also use the notation “Soft” for sources that are dominated by thermal emission components and “Hard” for spectra dominated by non-thermal emission.

\(^{8}\) http://pulsar.sternwarte.uni-erlangen.de/wilms/research/tbabs/
Figure 1. Left: Data-to-model ratio plots for all sources with a detected Fe Kα emission line. The model includes all fit-required components (i.e. thermal and non-thermal continuum emission, soft X-ray emission features), except the Gaussian component used to model the iron emission. Right: Data-to-model ratio plots for all sources with no iron line detection. All sources are included except for 4U 1626-67. Due to its unique nature – as an UCXB, X-ray pulsar – the analysis of this source is presented separately.

Figure 2. Data-to-model ratio plots for the two sources with a variable Fe Kα emission line.

3.5.1 4U 0513-40

The spectral continuum of 4U 0513-40 is well described by a combination of a soft MCD component and power-law tail, that dominates the emission above ∼2 keV. Absorption-like residuals centered around 0.5 keV were modeled using a gaussian absorption line and no other residual structure was identified. The combination of the three models yields a reduced χ² value of 1.12 for 163 dof. No iron emission line was detected. An upper limit for the EW of a Fe Kα line was estimated at ∼6 eV. The 0.5-60 keV source luminosity during the observation was ∼1.2×10³⁷ erg s⁻¹. Out of 1198 observations of the source by BeppoSAX, INTEGRAL and RXTE, 35 type I X-ray bursts have been detected for 4U 0513-40.

3.5.2 4U 0614+091

The source spectrum during this XMM-Newton observation was dominated by non-thermal emission modelled using a power-law model with a spectral index of ∼2.2. Low-energy residual structure indicated the potential presence of soft thermal emission which was modeled with a MCD model signifying emission from a truncated accretion disk with a temperature of ∼100 eV. Residuals around ∼6.6 keV reveal the presence of a strong iron emission line (see data-to-ratio plot in Figure 1), modeling the line with a gaussian results in δχ² of 390 for 3 dof. The Fe Kα line has an EW of ∼63 keV. Further modeling of emission (at ∼0.5 keV) and absorption-like (at ∼0.7 keV) features with an emission and one absorption Gaussian, respectively, yields a red. χ² value of 1.16. We also note the pres-
ence of narrow residuals in the 1.7-2.5 keV range. They, most likely originate from incorrect modeling of the Si and Au absorption in the CCD detectors by the EPIC pn calibration, which often results in the presence of emission and/or absorption features at ~1.84 keV, ~2.28 keV (Mg) and 2.4 keV (Mg). The features are not very pronounced and do not affect the quality of the fit or the aim of our analysis. Therefore, we have ignored them, but their respective energy channels are still included in our fits. 4U 0614+091 is a frequent type I X-ray burster with a reported period of ~17 d (Jenke et al. 2016).

3.5.3 2S 0918-549

The spectrum of 2S 0918-549 appears to be dominated by thermal emission, which is modeled using different thermal components, an MCD model (diskbb) with a temperature of ~0.6 keV and a spherical black body emitter of $T_{BB} = 1.2$ keV. Some further residual structure above 8 keV is modelled using a hard power-law tail. No iron emission line was detected, with an EW upper limit of ~7 eV. The best-fit model yields a red, $\chi^2$ value of 1.08 for 1848. A total of 7 type I X-ray bursts have been recorded out of 772 observations of the source, since 1995.

3.5.4 XTE J0929-314

While no available XMM-Newton, Chandra or NuSTAR during outburst, a 2002 outburst was observed by RXTE. We analyzed the longest of multiple observations taken during the outburst. The source spectrum, in the 3-30 keV range was modeled using a combination of MCD thermal emission and a power-law tail. The interstellar absorption cannot be constrained in this energy range and its value was frozen at the total galactic H I column density value (HI4PI Collaboration et al. 2016). No emission features where detected with a Fe Kα emission line EW upper limit of ~20 eV. No type I X-ray burst have been observed from this source.

3.5.5 4U 1543-624

During this 2001 XMM-Newton observation, we found that the spectrum is dominated by thermal emission which we model using a combination of MCD and spherical black body models. Strong and complex residuals in the sub-1 keV spectral region were modelled using two emission and one absorption Gaussian component. Due to degeneracy between interstellar adsorption column density value and the parameters of the absorption lines, the column density was frozen to its galactic value (indeed, proper modelling of the line-of-sight absorption in 4U 1543-624 requires addition local absorption with extra-solar abundances, see e.g. Juett et al. 2001). Due to their prominence the two instrumental absorption lines at 1.85 keV and 2.2 keV were modelled with two zero-width absorption lines, in order to achieve a satisfactory $\chi^2$ value. No iron emission was detected in the 6-7 keV region, with a tight EW upper limit of ~3 eV. We note that analysis of older (1997) RXTE observations, revealed the presence of a prominent Fe Kα emission line (see also analysis by Schultz 2003), for a similar continuum. The variability of the line in this source is mentioned here and briefly discussed in Section 4, but is thoroughly examined in a separate publication (Koliopanos et al. submitted to MNRAS). After, decades of consistent monitoring by numerous telescopes (since 1996 by ASM, INTEGRAL, Fermi-LAT, MAXI), the first type I X-ray burst for 4U 1543-624 was observed by MAXI in Feb. 2nd 2018 Serino et al. (2018).

3.5.6 IGR J17062-6143

IGR J17062-6143 is the newest confirmed UCXB source, with its orbital period determined by the recently launched Neutron Star.
During this observation the source was found in the "Soft" state, with a spectrum dominated by two thermal components, modeled using our standard combination of MCD ($kT \sim 0.7$ keV) and blackbody ($kT \sim 2.3$ keV) models. Pronounced absorption-like features (likely mismodelled absorption edges due to non-solar abundance of circum-source material) were modelled using Gaussian absorption lines. Strong emission-like residuals in the 6-7 keV region revealed the presence of a prominent, broad iron emission line located at $\sim 6.6$ keV, with a width of $\sim 0.6$ keV and an EW of $\sim 80$ eV. The final fit yields a $red_{\chi}^2$ value of 1.18 for 1748 dof. More than 1000 type I X-ray bursts have been detected from this source. During this observation its luminosity was estimated at $\sim 6 \times 10^{36}$ erg/s.

**3.5.8 XTE J1751-305**

The source was observed during a bright, soft state, the spectrum is well modelled using a MCD component with $kT \sim 0.9$ keV and a hotter thermal component with $kT \sim 3.5$ keV. No emission features were detected on top of the source continuum and the luminosity of the source during the observation was $\sim 10^{37}$ erg/s. Since detection in 2002 (Markwardt et al. 2002), no X-ray bursts have been detected for this source.

**3.5.9 Swift J1756.9-2508**

For the main analysis of this source we use the most recent (2018) XMM-Newton observation. Swift J1756.9-2508 was dominated by thermal emission likely originating in a hot disk and hot thermal emission from the NS surface. As per our analysis scheme we modelled the emission using a MCD component with $kT \sim 0.9$ keV and a spherical blackbody component with $kT \sim 3.5$ keV. No iron emission line was detected with a 1σ upper limit on the EW of a gaussian emission line of $\sim 5$ eV. Nevertheless, we note that in previous outbursts in 2007 and 2009 a very prominent iron emission line was detected in RXTE spectra of the source (see Patruno et al. 2010, for the iron emission in the 2009 observation). We have also analyzed the 2007 RXTE observation which we present in Table A1 in the appendix. As with 4U 1543-624 the variability in the presence of the iron line in this source is briefly discussed in Section 4 and more thoroughly inspected in a submitted paper by Koliopanos et al. (submitted to MNRAS). No type I X-ray bursts have been detected for Swift J1756.9-2508.

**3.5.10 XTE J1807-294**

The source was observed during a bright soft state, which we modelled using the MCD-sph. blackbody combination. No iron emission was detected in the 6-7 keV spectral region. A prominent emission-like feature at $\sim 1$ keV, was modelled using a Gaussian emission line model. No type I X-ray bursts have ever been recorded for this source.

**3.5.11 4U 1820-30**

4U 1820-30 is a known X-ray burster with a recurrence rate of 2-4 hr. For our analysis we selected a recent NuSTAR observation of the source. The source spectrum was dominated by non-thermal emission, modelled using a power law with a spectral index of $\sim 2$ and an exponential cutoff at $\sim 12$ keV. Low energy residuals, also revealed the presence of thermal emission, which was modelled using a MCD. A strong and broad iron emission line was detected and modelled with a Gaussian centered at $\sim 6.5$ keV with an EW of $\sim 50$ keV. The 0.5-60 keV source luminosity during this observation was $\sim 10^{38}$ erg/s.

**3.5.12 4U 1850-087**

With a spectrum dominated by two thermal components this source was also modelled with the combination of MCD and spherical blackbody models we use to describe the soft state in NS-XRBs. The soft component has a temperature of $\sim 0.5$ keV and the hot $\sim 2$ keV. As with many source in the UCXB sample, a multitude of mismodelled absorption edges (likely the result of non-solar abundances in the circum-source material) as well as emission-like features were modelled using simple Gaussians, without aiming at an interpretation. 4U 1850-087 has been monitored reasonably monitored for more than a decade. Four type I X-ray bursts have been recorded for this source, out of $\sim 1300$ observations.

**3.5.13 4U 1916-05**

4U 1916-05 is a well-known and well-studied UCXB-burster with type I X-ray burst recurrence rate of $\sim 6$ hr (e.g. Smale et al. 1988; Church et al. 1998; Botin et al. 2004; Díaz Trigo et al. 2006; Juett & Chakrabarty 2006; Heinke et al. 2013; Koliopanos et al. 2014). In our analysis of this 2004 observation of the source the spectral continuum was dominated by non-thermal emission, modeled with a power law of $\Gamma \sim 2$, we also detect a soft thermal component comnsumurate with an accretion disk with $kT \sim 0.1$ keV and an additional thermal-like component with a temperature of $\sim 1.5$ keV. We further detect the broad and prominent iron emission line reported by several previous authors. Our analysis indicates an emission line centered at $\sim 6.7$ keV with an EW of $\sim 60$ eV. We further detect narrow absorption-like features at $\sim 6.65$ and $\sim 6.95$ keV that are consistent with resonant absorption from FeXXV and FeXXVI ions, respectively, in agreement with the findings of Juett & Chakrabarty (2006), using Chandra data. The source 0.5-60 keV luminosity during this observation was $\sim 10^{37}$ erg/s.
3.5.14  M15 X-2

M15 X-2 (4U 2129+119) was observed in a hard state. The source emission is dominated by a power-law shaped spectrum (Γ~1.5, exponential cutoff at ~8 keV), while low-energy residuals also indicate the presence of thermal emission from a cool disk (KT~0.1 keV). No emission-like features were detected on top of the source continuum, with an upper limit for the EW of a Fe Kα line estimated at ~8 eV. One type I X-ray burst has so far been recorded for this source (Dieball et al. 2005), out of 162 observations (MINBAR3).

3.5.15  NGC 6440 X-2

This is the third confirmed UCXB inside a globular cluster (along with M15 X-2 and 4U 1820-30). Its spectrum was modelled using a simple power law. No additional broad components were required. Emission-like residuals were detected in the 6–7 keV energy range. Modelling the residuals with a Gaussian, improved the χ^2 value by a δχ^2 of 10.7 for 2 dof (the line width was frozen at 0.1 keV). The EW for the emission line was ~75 keV. No type I X-ray bursts have been recorded for NGC 6440 X-2.

3.5.16  4U 1626-67

4U 1626-67 is unique among UCXBs, as it is a highly magnetized (B~10^{12} G) NS and an X-ray pulsar. In this analysis we used a 2003 XMM-Newton observation. The source continuum was fitted with a power-law with a spectral index of ~0.8 and an exponential cutoff at ~8 keV. Below ~1 keV, the spectrum is dominated by thermal emission which was modeled using a MCD component with KT~0.4 keV. Narrow emission-like feature were also detected at ~0.6 keV and ~1 keV and were modelled using Gaussian emission lines. No iron line emission was detected during this observation. Nevertheless, we noted that after its 2010 luminosity increase and torque reversal, a faint emission Fe Kα emission line was detected in RXTE and Chandra data (e.g. Koliopanos & Gilfanov 2016). The Koliopanos & Gilfanov findings were confirmed by a 2015 NuSTAR observation (e.g. Iwakiri et al. 2019). We also analyze this observation and tabulate our findings in Table A1 in the Appendix. In the NuSTAR observation (which was also taken during the more luminous spin-up era) we detect a moderately bright iron emission line with an EW value of ~30 eV.

We note that due to the nature of this source – and despite our selection of the MCD model for the thermal emission in both observations – it is likely that it does not originate in the accretion disk and the iron line emission line is not the result of the standard coronal-disk reflection scenario modeled in Koliopanos et al. (2013). For these reasons, this source is discussed separately in Section 4 and its data-to-model ratio plot appears separately in Figure 3, for both epochs. One of the most well monitored X-ray binary, 4U 1626-67 has never been observed to produce X-ray bursts.

4 DISCUSSION

4.1  The spectral continuum

We have revisited X-ray observations of all known UCXBs. Our goal was not to retrace previous spectral analyses, but rather to model the spectral continuum in a consistent and physically motivated manner in order to draw conclusions on the presence or absence of the primary X-ray reflection feature in X-ray spectra, the iron Kα line and use it as a diagnostic of the chemical composition of their disk and donor star. Our analysis of the spectral continuum confirms a physically credible interpretation of the spectral shape for NS-XRBs, that has been noted in numerous previous studies (e.g. Barret 2001; Lin et al. 2007). From our sample of 16 confirmed UCXBs we found eight sources in the “Soft” state, i.e. dominated by hot two thermal component (for sources 2S 0918-549 and IGR J17062-6143 a faint power law tail is also detected), while the other eight were found in the “Hard” state, dominated by non-thermal emission and a cool MCD component (4U 1916-05 also features a hot thermal component, signifying a state transition).

During the soft state of accreting highly magnetized neutron stars, the accretion disk is expected to reach the NS surface. Indeed, all sources in these state yield best fit values for the inner disk radius in the 10–15 km range. A hot accretion disk extending to the surface of the NS. Furthermore, in all spectra we detect a secondary hotter thermal component (KT~1 keV) consistent with emission from the hot, optically thick boundary layer expected to form on the surface of the NS during this state. Non-thermal tails during this state are usually detected in spectra from telescopes that extend at energies above 10 keV. Nevertheless we did detect an additional power-law shaped component in the spectra of sources 2S 0918-549 and IGR J17062-6143 suggesting a likely transition state. The spectra of all sources found in the hard state were dominated by non-thermal emission, along with a clear detection of a soft MCD component. In all cases the accretion disk temperature is considerably smaller that the disk temperature in the soft state sources with the inner disk radius exceeded in the order of hundreds of km. These estimations are consistent with theoretical predictions of a truncated disk in hard state XRBs. The realistic quantities we derive from our best-fit values, increase the confidence in our analysis of the spectral continuum and consequently our estimations for the EW of the Fe Kα line.

4.2  Iron emission and X-ray diagnostics

We have detected prominent and broad iron Kα emission lines in six of the known UCXBs (see Figure 1, left). For all sources for which the emission line was detected – and for which additional data with adequate statistics were available (see appendix for extra observations that were checked) – we determined the stable presence of the emission line in their spectra. Another seven sources in the UCXB catalog showed no evidence of iron line emission (Figure 1, right) with tight upper limits on iron emission, in most case EW<10 eV. Similarly to the previous sample, all other available observations were inspected in order to confirm the absence of the Fe Kα line. The remaining three known UCXBs exhibited a variability in the presence of the iron line (Figures 2 and 3).

4.2.1  Non detection

With the help of our Monte Carlo simulation from Koliopanos et al. (2013), we can use the results of our analysis on the iron line detection, in order to evaluate the chemical composition of the accretion disk and donor star. The code models fluorescence Kα and Kβ lines for elements between Z=3 and 30 and estimates their EWs with respect to the total emission, which is a combination of both the primary and the reflected component. For this work we have

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Not to be confused with neighboring source 4U 2129+12
updated our code with the abundances by (Wilms et al. 2000)\textsuperscript{10} and atomic cross-sections from Grevesse & Sauval (1998), for consistency with the xspec modelling. The code simulates the abundances of C/O-rich disk by "converting" H and He into C and O. In practice we gradually reduce the solar-like abundances (by mass) of H and He, while increasing those of C and O by the same amount. The total number of nucleons is conserved, mass ratios of all other elements are kept fixed at their solar values and the C/O abundance ratio, also remains fixed. The position along this sequence of abundances can be give by the O/Fe ratio normalized to its solar value from (Wilms et al. 2000). The value of the O/Fe ratio corresponding to full "conversion" of H and He to C and O is 78.

To evaluate the absence of iron emission line in the spectra of our sources, we estimated the minimum value of the O/Fe ratio, in order to produce an Fe Kα line with an EW of 20 eV, which is the highest upper limit in our sample source with no iron detection (source: XTE J0929-314), for an incident power law with $\Gamma = 1.9$ (best-fit parameter for XTE J0929-314). Assuming an angle of 80$^\circ$ for the incident spectrum – which yields the lowest iron line EW for a given O/Fe ratio – we deduce that an O/Fe ratio of at least 12 is necessary in order to yield an iron emission line with EW <20 eV. The O/Fe ratio increases to 25 for a face-on incident spectrum ($\circ$). Incident spectra with lower spectral index or thermal primary emission (sources with thermal boundary layer emission at $kT_{\text{tris}1}$ keV), require O/Fe: 34 in order for the iron line to not be detected in their spectra at an EW<20 eV. Based on these estimations, the disappearance of the iron emission line from the spectra of the seven UCXBs: 4U 0513-40, 2S 0918-549, XTE J0929-314, XTE J1751-305, XTE J1807-294, 4U 1850-087 and 4U 2129+11 is the result of an O/Fe ratio at least an order of magnitude higher than the solar value, which can be interpreted as the result of a C/O or O/Ne/Mg donor in these sources.

\subsection{Persistent Kα emission line}

Six sources in the UCXB catalog feature a persistent iron emission line in their spectra, detected in multiple past observations (see Table 3 for the source with Fe Kα line detection and Table A2 in Appendix for alternative observations that we have inspected. Based on the findings of our simulations, if the iron emission lines are the result of disk reflection – further supported by the fact that all lines are considerably broadened – the disk and donor star must be dominated by helium. We also note two of the three sources that are also found in the soft-state feature an emission line with a considerably higher value of the EW (sources IGR J17062-6143 and 4U 1916-05). Our estimations (see e.g. Table 2 in Koliopanos et al. 2013) indicate that soft-state sources produce emission line with higher EW values (i.e. in the 150-250 eV range). This is primarily due to the shape of the incident spectrum – i.e. a power law with $\Gamma \geq 1.51$ vs a black body with kT$\sim$1.5 – 3 keV and is the result of higher available photons near the 7.1 keV K-shell absorption edge of iron. However, harder power-law shaped incident spectra (e.g. $\Gamma < 1$, usually found in accretion column emission) can produce Fe Kα line with similar EW to the black body incident spectrum. While, the seeming agreement between our observational analysis and the simulation results is encouraging, it must be considered very cautiously, as there are several other parameters involved, including the disk-corona geometry, viewing angle and disk ionisation state.

\subsection{Variable presence of the Fe Kα emission line}

Examination of the rich observational archive of the UCXB source catalog revealed three sources for which the presence of the iron Kα line varies through the years. This is a very intriguing discovery, since the variability of this process – i.e. screening of the iron line by carbon and oxygen – had been predicted by our initial analysis in Koliopanos et al. (2013). More specifically, in C/O dominated disks the screening efficacy of the two elements depends entirely on whether they are fully ionized or not. When oxygen (and therefore carbon) become fully ionized in the disk, the EW of iron line is expected to return to each initial value, which is largely determined by the abundance of iron in the disk. In the Koliopanos et al. paper, simple analytical arguments were used to predict a luminosity dependence of the iron line variability. Under the assumption that the ionization state of the disk mostly depends on the accretion rate, it was predicted that critical a luminosity value for the variability of the iron line presence was at $\sim 10^{-3}$ erg/s. Nevertheless, sources 4U 1543-624 and Swift J1756.9-2508 were observed at the similar luminosity ($<10^{-2}$ erg/s) and at similar spectral states. A more detailed study of the these two sources and the origin of the iron line variability is presented in a separate work by Koliopanos et al. (submitted to MNRAS).

The third source with a variable presence of the iron line is 4U 1626-67. This is an exceptional source – even within the already extraordinary UCXB population, as it is the only UCXB which has a highly magnetized NS accretor. It is a persistent X-ray pulsar with a known magnetic field of $B=10^{12}$ G, based on detection of cyclotron resonant scattering features, (e.g. Iwakiri et al. 2019). The iron line variability on this source was first reported by Koliopanos & Gilfanov (2016). Using archival data it was demonstrated that the emission line – which is present during high-luminosity spin-up periods – disappears when the luminosity drops, as the source goes into a spin-down epoch. It was further argued that this behavior was due to a geometric effect, the result of change in the emission diagram of the accretion column, which in turn is luminosity dependent (see e.g. Fig.1 of Schönherr et al. 2007, and references therein).

In this work we revisited the XMM-Newton observation for spectral analysis during the spin-down period and the recent NuSTAR observation taken during the current spin-up phase. We note that our use of a MCD component for the modelling of the soft thermal emission does not necessarily signify emission from the inner part of an accretion disk heated due to viscous dissipation of gravitational energy. Indeed, the best fit value of the inner disk radius for the MCD model is of the order of 10-80 km for the two epoch; more than two orders of magnitude smaller than the expected size of the NS magnetosphere for the strength of its magnetic field and the source luminosity (assuming 20% efficiency; see also estimations in Koliopanos & Gilfanov 2016). It is very likely that the thermal component originates in optically thick material in the vicinity of the magnetosphere, which is further heated due to illumination from the central source emission – a phenomenon that is often detected in X-ray pulsars (see Endo et al. 2000 and Hickox et al. 2004 for a detailed description of this configuration and Koliopanos & Vasilopoulos 2018 for a recent observational example).

Based on this scheme, the reasoning (that was also put forward in Koliopanos & Gilfanov 2016) is that the disappearance of the iron line during the low-luminosity era, is due to significantly

\textsuperscript{10} With abundances from Anders & Grevesse (1989) for elements not included in Wilms et al.
reduced illumination of the optically thick magnetospheric material, which in turn is the result of the changing beam pattern. This is further highlighted by the less luminous and significantly cooler soft emission, during the low-luminosity XMM-Newton observation (Table 1). The evolution to a fan-beam pattern emission, results in full illumination and heating of the optically thick material, and the appearance of the iron line, during the high luminosity phase, observed with NuSTAR. We ran our code for a beam with a 20° opening angle aimed at an optically thick rectangular slab using realistic abundances for a C/O WD donor, predicted by Gil-Pons & García-Beorro (2001), and the atomic cross-sections of Grevesse & Sauval (1998). If the materially is illuminated in a face-on configuration we can reproduce an emission line with EW of ~50. If the materially is illuminated in a face-on configuration we can reproduce an emission line with EW of ~50.

4.3 Type I X-ray bursts and optical spectroscopy

We made an effort to comprehensively report the bursting activity of all sources in the UCXB catalog, presented in Table 3. The recurrence rate of type I X-ray bursts can also indicate the chemical composition of the accreted material. Frequent bursts can be attributed to accretion of helium dominated material and/or residual hydrogen. While sparse or no bursts – particularly in persistent sources (find them all and mention) – can be considered indicative of C/O rich material with only limited amount of residual helium and/or hydrogen. In addition to their regularity, the characteristics of thermonuclear X-ray bursts – predominantly their duration and light-curve shape – are heavily dependent on the chemical composition of the accumulated material which in turn affects the nuclear burning. For instance, hydrogen burns to helium via the CNO cycle and helium burns to carbon through the triple-alpha process. In broad terms, type I X-ray bursts can be divided into three categories based on their duration. Short bursts (~10-100 s, associated with surface, unstable H and He burning, see reviews by Lewin et al. 1993 and Strohmayer & Bildsten 2006), intermediate bursts (~15-40 m most likely powered by the burning of a thick layer of helium, e.g. Cumming et al. 2006) and the so-called superbursts (~1 day, powered by carbon burning, e.g. Kheck et al. 2008).

All sources in the UCXB catalog – for which no iron line is detected in their spectra (including the variable sources) – exhibit sparse type I X-ray bursts or no bursts at all. The source with most bursts detected is 4U 0513-40 (35 bursts detected in over a decade of monitoring). Out of the 10 sources with no iron emission features, six are persistent sources (4U 0513-40, 2S 0918-549, 4U 1543-624, 4U 1850-087, 4U 2129+11 and 4U 1626-67) and four are transient (XTE J0929-314, XTE J1751-305, Swift J1756.9-2508, XTE J1807-294). On the other hand, the five out of six UCXBs with prominent and persistent iron emission lines are frequent bursters with hundreds of type I X-ray bursts recorded and some with estimated recurrence rates in the order of days or hours. Four of these five sources, are persistent emitters (4U 0614+091, 4U 1728-34, 4U 1820-30, 4U 1916-05), while the fifth (IGR J17062-6143) is a transient source which has produced type I X-ray bursts during both of its outbursts. The sixth UCXB with an iron line detection is NGC 6440 X-2, which is a transient source. No bursts have been observed from this source, but it is important to note that NGC 6440 X-2 exhibits faint outbursts with very short duration, that usually go undetected by all-sky monitors (Altamirano et al. 2010), for this reason there are only few available observations for this source.

In addition to their high recurrence rates, the burst characteristics of sources 4U 1820-30 (e.g. Bildsten 1995; Cumming 2003; Galloway et al. 2008), 4U 1916-05 (e.g. Galloway et al. 2008), 4U 1728-34 (e.g. Galloway et al. 2008; Misanovic et al. 2010), 4U 0614+091 (e.g. Linares et al. 2012) and IGR J17062-6143 (e.g. Keek et al. 2017) are also consistent with helium burning. Most UCXB companion stars and accretion disks are too faint for optical spectroscopy, 4U 1916-05 has optical confirmation of a He-rich donor (Nelemans et al. 2006), while tentative optical evidence for a C/O companion have been put forward for 4U 1626-67, 2S 0918-549 (orbit period and low mass-transfer rate also consistent with low-entropy C/O white dwarf donor Heinke et al. 2013) and 4U 1543-624 (Nelemans et al. 2004; Werner et al. 2006) and FUV for 4U+2129+11 (C and He lines Dieball et al. 2005). On the other hand, contrary to our designation as a He-rich source, Nelemans et al. (2004) and Werner et al. (2006) have proposed a C/O-rich donor for 4U 0614+091, based on the presence of C and O emission lines on optical spectrum from the VLT. Our re-classification, however, not only handily explains its persistent bursting activity, but is also in agreement with indications for a He-rich donor based on arguments on disk stability and evolution (Heinke et al. 2013). FUV (Homer et al. 2002) and optical (Werner et al. 2006) spectroscopy of 4U 1626-67 supports the presence of C/O-rich donor, in agreement to our classification. However, Heinke et al. (2013) argue that the orbital period and persistent accretion of the source can best be explained by He-star models rather than a C/O-rich donor.

4.4 X-ray spectroscopy in the bibliography

Meticulous scrutiny of the X-ray spectral continuum of 4U 0513-40, 4U 0614+091, 2S 0918-549 and 4U 1850-087 – using moderate (ASCA, BeppoSAX and XMM-Newton EPIC) and high resolution instruments (Chandra and XMM-Newton grating spectrometers) – have revealed the presence of unusually strong absorption edges, indicating highly non-solar composition of the local interstellar medium, attributed to C/O or O/Ne/Mg-rich donors (e.g. Paerels et al. 2001; Juett et al. 2001; Juett & Chakrabarty 2003). However, analysis of later observations, yielded standard solar-like abundances, revealing a temporal variability of the effect and thus indicating that the apparent non-solar abundances could be the result of fluctuations in the ionization state of the surrounding material (e.g. Juett & Chakrabarty 2005; Schward et al. 2010), rather than the result of non-solar composition. Detection of broad emission-like features have also been detected in sources 4U 0614+091 (Madej et al. 2010), 4U 1453-624 (Madej & Jonker 2011) and 4U 1626-67 Krauss et al. (2007) and have been attributed to emission from over-abundant carbon, oxygen and/or neon in the accretion disk material (e.g. Madej et al. 2014). Nevertheless, prominent emission-like features in the < 1 keV energy range, have been observed in the spectra of numerous NS- and BH-XRBs of all types, during different states and at different mass accretion rates (e.g. Boirin & Parmar 2003; Díaz Trigo et al. 2006; Ng et al. 2010; Madej et al. 2014) and are not necessarily an indication of non-solar composition.

An interesting point is raised by the modelling of 4U 0614+091 by Madej et al. (2014). In this work, they use a version of the XILIVER X-ray reflection code (García & Kallman 2010; García et al. 2011; García et al. 2013) modified in order to simulate reflection by C/O-rich material (the authors refer to this...
version of their code as XILLVER$_{\alpha}$). They successfully model the soft emission-like features as well as the iron K$_\alpha$ emission line and argue that the soft features are due to a C/O-rich accretion disk. This finding seemingly contradicts the findings of our own MC simulations which clearly indicate the screening of the iron line (primarily) by the overabundant oxygen. However, it is important to note that XILLVER$_{\alpha}$ does not realistically H and He-poor chemical composition, but rather simulates this by artificially increasing the abundance of all elements apart from H, He, C and O by $\times 10$ times and then further increases the abundances of C and O producing a grid of abundance patterns in order to fit the spectra of 4U 0614+091. In the two observations where their fit constrains the C/O abundance, they report a value ranging between 130 to 160$\times$ their solar value. However, based on their scheme for mimicking the C/O-rich disk, their actual O/Fe ratio is 13-16$\times$ its solar value, at least five times lower than the O/Fe ratio of an actual H-poor, C/O-rich disk (i.e. $\sim$80. Koliopanos et al. 2013; Koliopanos et al. 2014 and this work). Furthermore, the accretion disk simulated by XILLVER$_{\alpha}$ in Madej et al. is still largely dominated by hydrogen and helium, rather than carbon and oxygen – which significantly affects the ionization state of the disk. On the other hand, while our own simulation features a realistic disk composition, it does not self-consistently estimate the ionization state of the C/O-rich disk. A combination of the merits of our own simulations and the highly sophisticated model of García & Kallman will be attempted in a future project.

5 CONCLUSIONS

The analysis of the X-ray spectra of all known UCXBs – using the predictions of the X-ray reflection code developed in Koliopanos et al. (2013) – has enabled us to draw potential conclusions for the chemical composition of their accretion disks and donor star. We found that all UCXBs that feature a prominent iron K$_\alpha$ in their X-ray spectra, that is persistent over multiple observations, also exhibit a rich and recurrent bursting activity. On the other hand, all UCXBs for which the iron line is not detected in all or most of their spectra, also have few or no type I X-ray bursts detected over more than a decade of monitoring. Based on the strong correlation between the strength of the Fe K$_\alpha$ emission line and the abundance of C and O in the accretion disk material – demonstrated in Koliopanos et al. (2013) – and the correlation between the abundance of H and He in the recurrence rate of short and intermediate type I X-ray bursts, we argue that there is a strong likelihood that all known UCXBs with persistent iron emission have He-rich donors, while those that do not, likely have C/O or O/Ne/Mg-rich donors.

If confirmed, this result can have profound implications in our understanding of compact binary evolution especially since standard population synthesis models tend to produce an overwhelming majority of He-rich systems rather than C/O-rich systems (e.g. Nelemans et al. 2010). Comparison of our conclusions with assessments based on optical and X-ray spectroscopy returned positive results, but also some tensions. We also found indications of the iron line variability in C/O-rich disks, predicted in Koliopanos et al. (2013). This finding is discussed in detail in a separate publication. On the other hand, it becomes evident that an increase in the sophistication of our X-ray reflection models is required concerning the problem of non-solar abundances and disk ionization. We therefore only regard the results of this work as encouraging and intriguing and conclude that they certainly justify further exploration.

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REFERENCES

Altamirano D., et al., 2010, ApJ, 712, L58
Amaro-Seoane P., et al., 2017, arXiv e-prints, p. arXiv:1702.00786
Anders E., Grevesse N., 1989, Geochimica Cosmochimica Acta, 53, 197
Arnaud K. A., 1996, in Jacoby G. H., Barnes J., eds, Astronomical Society of the Pacific Conference Series Vol. 101, Astronomical Data Analysis Software and Systems V. p. 17
Ballantyne D. R., Ross R. R., Fabian A. C., 2001, MNRAS, 327, 10
Barret D., 2001, Advances in Space Research, 28, 307
Basko M. M., Sunyaev R. A., Titarchuk L. G., 1974, A&A, 31, 249
Belczynski K., Taam R. E., 2004, ApJ, 603, 690
Bildsten L., 1995, ApJ, 438, 852
Bildsten L., Deloye C. J., 2004, ApJ, 607, L119
Boirin L., Parmar A. N., 2003, A&A, 407, 1079
Boirin L., Parmar A. N., Barret D., Paltani S., Grindlay J. E., 2004, A&A, 418, 1061
Brandt S., Castro-Tirado A. J., Lund N., Drennin V., Lapshov I., Sunyaev R., 1992, A&A, 262, L15
Cackett E. M., et al., 2010, ApJ, 720, 205
Chakrabarty D., 1998, ApJ, 492, 342
Chakrabarty D., Morgan E. H., 1998, Nature, 394, 346
Church M. J., Parmar A. N., Balucinska-Church M., Oosterbroek T., dal Fiume D., Orlandini M., 1998; A&A, 338, 556
Cornish N., Robson T., 2017, in Journal of Physics Conference Series. p. 012024 (arXiv:1703.09858), doi:10.1088/1742-6596/840/1/012024
Cumming A., 2003, ApJ, 595, 1077
Cumming A., Macbeth J., in ‘Zand J. J. M., Page D., 2006, ApJ, 646, 429
Degenaar N., Miller J. W., Wijnands R., Altamirano D., Fabian A. C., 2013, ApJ, 767, L37
Deloye C. J., Bildsten L., 2003, ApJ, 598, 1217
Deloye C. J., Bildsten L., 2005, ApJ, 624, 934
Díaz Trigo M., Parmar A. N., Boirin L., Méndez M., Kaastra J. S., 2006, A&A, 445, 179
Dieball A., Knigge C., Zurek D. R., Shara M. M., Long K. S., Charles P. A., Hannikainen D. C., van Zyl L., 2005, ApJ, 634, L105
Done C., Gierliński M., Kubota A., 2007, A&ARv, 15, 1
Endo T., Nagase F., Mihara T., 2000, PASJ, 52, 223
Fabian A. C., Rees M. J., Stella L., White N. E., 1989, MNRAS, 238, 729
Fiocchi M., Bazzano A., Nateluchii L., Landi R., Ubertini P., 2011, MNRAS, 414, L41
Galloway D. K., 2006, in D’Amico F., Braga J., Rothschild R. E., eds, American Institute of Physics Conference Series Vol. 840, The Transient Milky Way: A Perspective for MIRAX. pp 50–54 (arXiv:astro-ph/0604345), doi:10.1063/1.2216602
Galloway D. K., Chakrabarty D., Morgan E. H., Remillard R. A., 2002, ApJ, 576, L137
Galloway D. K., Munro M. P., Hartman J. M., Psaltis D., Chakrabarty D., 2008, ApJS, 179, 360
Galloway D. K., Yao Y., Marshall H., Misanovic Z., Weinberg N., 2010, The Astrophysical Journal, 724, 417
Garcia J., Kallman T. R., 2010, ApJ, 718, 695
Garcia J., Kallman T. R., Mushotzky R. F., 2011, ApJ, 731, 131
Garcia J., Dauser T., Reynolds C. S., Kallman T. R., McClintock J. E., Wilms J., Eikmann M., 2013, ApJ, 768, 146
George I. M., Fabian A. C., 1991, MNRAS, 249, 352
Gil-Pons P., García-Berro E., 2001, A&A, 375, 87
Gilfanov M., 2010, in Belloni T., ed., Lecture Notes in Physics, Berlin Springer Verlag Vol. 794, Lecture Notes in Physics, Berlin Springer Verlag. p. 17, doi:10.1007/978-3-540-76937-8_2
Table A1. Best fit parameters for the continuum emission spectra of the three UCXBs with variable iron line emission. 4U 1626-67 – a high-B NS, X-ray pulsar – is tabulated separately. All errors are in the 1σ confidence range.

| Source                  | nh     | E_planck | R_in_disk | K_BB | R_IN | L_X | 10^22 dBB  | r_x^2/dof |
|-------------------------|--------|----------|-----------|------|------|-----|-----------|----------|
| 4U 1543-624 (1997)      | 0.29^a | 0.89^b   | 11.4^b   | 4.32^b | 6^b  | 1.53±0.01 | 0.32±0.06 | 1.61  | 0.64±0.04 |
| Swift J1756.9-2508 (2007) | 0.01^a | 1.85^a   | 6.3^b    | -    | -    | -   | 4.15±0.04 | 0.10±0.05 | 4.53  | 0.62±0.32 |

a) R_in_disk (the inner radius of the accretion disk in km) is inferred from dBB model, by solving K_BB=(R_IN/D_IN)^2 cos i, for R_IN. ‘K_BB’ is the normalisation of the dBB model, D_IN is distance in units of 10 kpc and i is the inclination. In all sources this was assumed to be 60°, with the exceptions of 4U 1916-05 and 4U 0513-40 (where i is set to 85°). With the exception of XTE J19029-314 (for which the K estimation has considerably high 1σ error bars), errors in radius estimation are dominated by the 1σ errors in the distance estimation (see Table 1).

b) Power-law component normalisation constant: photons keV cm^{-2} s^{-1} at 1 keV.

c) Size of the spherical black body component (bbbody model), estimated from K_BB=R_IN^2/D_IN^2, where K_BB is the normalization parameter of the bbbody model.

d) Luminosity in the 0.5-60 keV range, extrapolated from the best-fit model.

e) Emission and/or absorption-like features detected < 1 keV were modelled using a combination of Gaussian absorption lines. For justification and details see Section 3.4.

f) Parameter frozen at total galactic H I column density (HI4PI Collaboration et al. 2016).

g) There is considerably uncertainty in the distance estimation for these two sources. Radius is estimated for a distance of 7 kpc (Wang & Chakrabarty 2004 for 4U 1543-624 and 8 kpc for 4U 1626-67 (4-13 kpc; Chakrabarty & Morgan 1998). Error bars are estimated from the 1σ errors for the best-fit value of R_IN.

h) With an additional "constrained" broken power law (p1≤2.5 and E_b=20 keV). This empirical model for high energy tails of NS XRBs in soft state, is often used in broadband X-ray spectroscopy (see Lin et al. 2007 and Koliopanos et al. submitted for more details). In the table we tabulate the value of p2 for the spectral index value.

Table A2. Best fit parameters for iron line emission in the three UCXBs with variable line detection. 4U 1626-67 – a high-B NS, X-ray pulsar – is tabulated separately. The errors are 1σ.

| Model parameter | 4U 1543-624 (1997) | Swift J1756.9-2508 (2007) | 4U 1626-67 (2010) |
|-----------------|-------------------|----------------------------|-------------------|
| Iron Line       |                    |                            |                   |
| Central E (keV) | 6.58±0.21^c        | 6.58±0.06                  | 6.76±0.03         |
| Width σ (keV)   | 0.6±0.31^d         | 0.1^d                      | 0.19±0.04         |
| Flux (10^{-3} ph cm^{-2} s^{-1}) | 9.5±3.5          | 42.6±4.60                 | 13.4±1.69        |
| EW (eV)         | 118±50             | 173±18.5                  | 30.1±3.85        |

^c 10^{-3} ph cm^{-2} s^{-1}.

^d Parameter frozen at minimum spectral resolution value.

Figure A2. 4U 0614-091: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A3. 2S 0918-549: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.
Figure A4. XTE J0929-314: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A5. 4U 1543-624 (2001): Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A6. 4U 1543-624 (1997): Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A7. 4U 1626-67: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A8. IGR J17062-6143: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A9. 4U 1728-34: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.
Figure A10. XTE J1751-305: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A11. Swift J1756.9-2508 (2007): Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A12. Swift J1756.9-2508 (2018): Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A13. XTE J1807-294: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A14. 4U 1820-30: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A15. 4U 1850-087: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.
Figure A16. 4U 1916-05: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A17. M15 X-2: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.

Figure A18. NGC 6440 X-2: Unfolded spectrum. Energy and data-vs-model ratio plot, for only the continuum model.