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First results from the use of the relativistic and slim disc model SLIMULX in XSPEC

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Abstract. Ultra-Luminous X-ray sources (ULXs) are accreting black holes for which their X-ray properties have been seen to be different to the case of stellar-mass black hole binaries. For most of the cases their intrinsic energy spectra are well described by a cold accretion disc (thermal) plus a curved high-energy emission components. The mass of the black hole (BH) derived from the thermal disc component is usually in the range of 100-1000 solar masses, which have led to the idea that this might represent strong evidence of the Intermediate Mass Black Holes (IMBH), proposed to exist by theoretical studies but with no firm detection (as a class) so far. Recent theoretical and observational developments are leading towards the idea that these sources are instead stellar-mass BHs accreting at an unusual super-Eddington regime. In this paper we briefly describe the model SLIMULX that can be used in XSPEC for the fit of thermal spectra of slim discs around stellar mass BHs in the super-Eddington regime. This model consistently takes all relativistic effects into account. We present the obtained results from the fit of the X-ray spectra from NGC 5408 X–1.

Key words: Accretion, accretion-discs – Black hole physics – Relativistic processes – X-rays: general

1. Introduction

Ultra-Luminous X-ray sources (ULXs) are point-like, off-nuclear, extra-galactic sources, with observed X-ray luminosities ($L_X \geq 10^{39}\,\mathrm{erg\,s^{-1}}$) higher than the Eddington luminosity for a stellar-mass black-hole ($L_X \approx 10^{38}\,\mathrm{erg\,s^{-1}}$). The true nature of these objects is still debated (Feng & Soria, 2011; Fender & Belloni, 2012) as there is still no unambiguous estimate for the mass of the compact object hosted in these systems.

Assuming an isotropic emission, in order to avoid the violation of the Eddington limit, ULXs might be powered by accretion onto Intermediate Mass Black

Holes (IMBHs) with masses in the range $10^2 - 10^5\,\mathrm{M}_\odot$ (Colbert & Mushotzky, 1999; Greene & Ho, 2007; Farrell et al., 2009). Recently, some studies have shown evidence of some ULXs being Black Hole Binaries (e.g. M 82 X–2; Kong et al. 2007; Caballero-García et al. 2013a). Later it was shown that M 82 X–2 is a binary but accreting onto a neutron star (Bachetti et al., 2014). It is suggested that ULXs are also powered by accretion onto stellar-mass BHs ($< 100\,\mathrm{M}_\odot$) at around or in excess of the Eddington limit (e.g. Colbert & Mushotzky 1999; Fabrika & Mescheryakov 2001; King et al. 2001; Fabbiano 2006; Poutanen et al. 2007; Liu et al. 2013).

Initially, they were supposed to be the IMBHs originating from low-metallicity Population III stars (Madau & Rees, 2001). Nevertheless, they are not spatially distributed throughout galaxies as it would be expected. On the other hand, IMBHs may be produced in runaway mergers in the cores of young clusters (Portegies Zwart et al., 2004). In such cases, they usually stay within their clusters. It has been found (Poutanen et al., 2013) that all brightest X-ray sources in the Antennae galaxies are located nearby the very young stellar clusters. NGC 5408 X–1 is also located nearby a young stellar association (Grisé et al., 2012). These studies concluded that these sources were ejected in the process of formation of stellar clusters in the dynamical few-body encounters and that the majority of ULXs are massive X-ray binaries with the progenitor masses larger than $50\,\mathrm{M}_\odot$. Currently, it is thought that only a handful of ULXs could be considered as potential IMBHs (ESO 243-49 HLX-1 between a few others; Farrell et al. 2009; Sutton et al. 2012).

In this paper we analyze one of the best available spectra from the ULX NGC 5408 X–1 obtained so far including the model `SLIMULX`[1] developed for fitting of thermal spectra of slim-discs around stellar mass BHs in the super-Eddington regime. We first introduce important observational results obtained for NGC 5408 X–1 so far in Sec. 1.1. Afterwards we give brief descriptions of the accretion disc theory both using standard and slim-disc configurations (Sec. 2), in order to justify the use of the latter in the case of NGC 5408 X–1. Finally, we present and discuss the analysis and results obtained by using `SLIMULX` (Sec. 3).

1.1. NGC 5408 X–1

The ULX in NGC 5408 X–1 was discovered with the *Einstein* observatory (Stewart et al., 1982) and its *soft excess* found with *ROSAT* (Fabian & Ward, 1993). It is located in a close-by (D = 4.8 Mpc, Karachentsev et al. 2003) small (size of 2.2×1.1 kpc) star-burst galaxy and at ≈20 arcsec from its centre. NGC 5408 X–1 is very bright, with a peak X-ray luminosity in the (0.3-10 keV) energy range of $\mathrm{L_X} = 2\times10^{40}\,\mathrm{erg\,s^{-1}}$. Strohmayer & Mushotzky (2009) found a QPO in its PDS centred at 0.01 Hz and inferred a mass for the BH in the range of $10^3 - 10^4\,\mathrm{M}_\odot$. On the other hand, Middleton et al. (2011) proposed a much

[1] **http://stronggravity.eu/results/models-and-data/**

smaller mass ($10^2\,\mathrm{M}_\odot$) in base of the QPO and the timing properties. They proposed that NGC 5408 X–1 is accreting in a super-Eddington regime and that the QPO is analogous to the ultra-Low-Frequency QPO seen occasionally in a few black hole binaries (BHBs). More recently, Dheeraj & Strohmayer (2012) studied the timing and spectral properties of NGC 5408 X–1 and have found that the QPO frequency is variable (within the frequency range of 0.0001-0.19 Hz) and that the spectral properties are approximately constant. They suggested that NGC 5408 X–1 is accreting in the *saturation regime* (increase of the QPO frequency with constant disc flux and power-law photon index) frequently observed in BHBs (Vignarca et al., 2003). On the other hand, based on the comparison with the case of BHBs but in the framework of the accretion states around BHs Caballero-García et al. (2013b) studied its spectral-timing properties during the same time-lapse as done by Dheeraj & Strohmayer (2012) (i.e. 6 yrs) and found a close similarity with the hard-intermediate state of BHBs but accreting at a much higher luminosity. Future work will help to discern between the two proposed different scenarios.

2. The X-ray properties from Ultra-luminous X-ray Sources

The spectra of ULXs show a power-law spectral shape in the 3-8 keV spectral range, together with a high-energy turn-over at 6-7 keV (Stobbart et al., 2006; Gladstone et al., 2009; Caballero-García & Fabian, 2010), and a *soft excess* at lower energies (e.g. Kaaret et al. 2006). This *soft excess* can be modelled by emission coming from the inner accretion disc and is characterized by a low inner disc temperature of ≈0.2 keV. This is expected if the BHs in these sources are indeed IMBHs (Miller et al., 2004). *Other explanations for the soft excess imply a much smaller mass for the BH in these sources, based on the idea that the accretion in the disc is not intrinsically standard, in contrast to the majority of BHBs (e.g. see Kajava & Poutanen 2009).*

2.1. The standard accretion disc theory

The low inner disc temperatures found for some ULXs were initially interpreted as an evidence for the presence of IMBH (Miller et al., 2004). In the standard disc-black body model (i.e. Multi-Color Disc Blackbody or MCD; Makishima et al. 1986, 2000), which is an approximation of the real standard accretion disc theory, the bolometric luminosity from the accretion disc is calculated as:

$$L_{\rm bol} = 4\pi (R_{\rm in}/\zeta)^2 \sigma (T_{\rm in}/\kappa)^4 \tag{1}$$

Here $\kappa \approx 1.7$ (Shimura & Takahara, 1995) is the ratio of the color temperature to the effective temperature, or "spectral hardening factor", and ζ is a correction factor taking into account the fact that $T_{\rm in}$ occurs at a radius somewhat larger than $R_{\rm in}$ (Kubota et al. 1998 give $\zeta = 0.412$). However, a recent spectral study of the spectral variability from a sample of ULXs, including NGC 5408 X–1 (Kajava & Poutanen, 2009), has shown that the *soft excess* (i.e. the disc component fitted in the spectra) from NGC 5408 X–1 does not follow Eq. 1 but $L_{\rm bol} \propto T_{\rm in}^{-3.5}$. *This in contrast to what is found for many BHBs and might indicate that the standard accretion disc theory is not a proper interpretation in the case of NGC 5408 X–1. This implies that the hypothesis on which the IMBH idea is relying (i.e. standard accretion disc theory and the presence of a cold disc) are not valid and it might indicate that the BH in NGC 5408 X–1 is not an IMBH.*

2.2. The SLIMULX model

Our analysis is based on the SLIMULX model. SLIMULX is an additive model for thermal continuum emission at high accretion rates to be used with the X-ray spectral-fitting tool XSPEC. The model provides spectral distribution of black-body radiation that is supposed to be emitted from the surface of a **relativistic** slim accretion disc (Abramowicz et al., 1988). Artemova et al. (2006) found a solution for slim accretion discs around BHs considering the optically thick/thin transition of the opacity and using a pseudo-Newtonian potential. We used the more recent numerical solutions of radial disc structure equations of Sądowski et al. (2011) which also include advection of matter and heat for a non-Keplerian rotation but throughout the geometrically vertically extended disc and considering a fully relativistic scenario. Because the geometrical thickness of the disc can be considerable, the model estimates the location of the effective photosphere and computes the radiation transport in Kerr space-time from that place with all relativistic effects properly calculated.

The SLIMULX model targets luminous sources that accrete at higher rates and for which the thin disc approximation becomes invalid. The higher the accretion rate, the higher departure from the standard (thin disc) temperature profile is as the advection of heat becomes more important and the more is the disc peak emission shifted inwards due to advection making the flow less radiatively efficient. The radial profile of cooling flux in the inner disc regions for super-Eddington accretion rates deviates from standard $\propto r^{-0.75}$ dependence to $\propto r^{-0.5}$. Such behaviour is valid for all values of the viscosity parameter α. However, the higher the value of α, the earlier advection affects the disc emission.

The final model spectrum is built as a sum of the local contributions from all parts of the disc surface. Some (inner) parts of the disc may, however, be hidden to the observer because they can be effectively shielded by outer parts of the geometrically thick disc. The importance of this effect grows with accretion rate and with observer inclination. In the most extreme situation the observer may be completely shielded from the inner hottest and most energetic parts of the disc being able to see only relatively cool and more distant part of the disc surface. The local contributions to the spectrum are in the frame co-moving with the disc surface modelled as a simple multi-color black-body. The user has a manual control over the overall hardening factor.

The present version of SLIMULX model comes in a form of a FITS table with pre-calculated spectra and a small routine which reads the data and produces the final spectrum in terms of interpolation in the parameter space. For five different values of α-viscosity and three different values of scale-height modifier, the table contains extensive three dimensional grids of spectra by varying the spin, luminosity and inclination. The three parameters are varied within the range of their limits on different types of logarithmic scales to ensure that the spectra make roughly equal changes between any two adjacent steps.

3. Observations and data reduction

For the spectral analysis we used only the *XMM-Newton*/EPIC pn camera, in order to avoid issues due to cross-calibration effects. Additionally, the EPIC pn camera has a higher effective area (i.e. double) than each one of the *XMM-Newton*/MOS cameras and has sufficient statistics for the spectral fitting. We used only the data from the ObsID num. 0653380201, since it has the highest number of counts. We applied the standard time and flare filtering (rejecting high-background periods of rate $\geq$12 counts/s). We filtered the event files, selecting only the best-calibrated events (pattern$\leq$4 for the pn), and rejecting flagged events (flag= 0). We extracted the flux from a circular region on the source centred at the coordinates of the source and radius 49 arcsec (the same as used by Gladstone et al. 2009). The background was extracted from a circular region, not far from the source.

We built response functions with the *Science Analysis System* (SAS) tasks `rmfgen` and `arfgen`. The background-subtracted spectra was fitted with standard spectral models in XSPEC 12.9.0 (Arnaud, 1996). All errors quoted in this work are 68% (1σ) confidence. The spectral fits were limited to the 0.3-8 keV range, in order to minimize the effects of the background selection. The spectra were rebinned in order to have at least 100 counts for each background-subtracted spectral channel in order to perform the chi-squared fitting and to avoid oversampling of the intrinsic energy resolution by a factor larger than 3.

4. Spectral analysis and results

As found in previous studies (Caballero-García et al., 2013b), the X-ray spectrum of NGC 5408 X–1 can be modelled by a continuum formed by an absorbed (curved) power-law describing the hard X-ray emission plus a soft X-ray emission component from a cold accretion disc in the Standard Thin Accretion Disc (hereafter referred to as SDT). Here we consider a simple (non-curved) absorbed power-law since we restrict the spectral analysis to $\leq$8 keV. We obtained a poor fit ($\chi^2/\nu = 255/100$) with residuals in the form of broad emission lines at en-

Table 1. Results from the spectral analysis.

Spectral parameter	Value
$N_{\rm H}$ ($\times 10^{22}$) (cm^{-2})	0.143$\pm$0.002
kT_1 (keV)	1.00$\pm$0.02
kT_2 (keV)	0.22$\pm$0.02
M (M$_\odot$)	5.7$\pm$0.3
a/M	0.99
$L_{\rm disc}/L_{\rm EDD}$	2.9$\pm$0.4
θ_0 (deg.)	$\leq$26
D (kpc)	4 800
κ	1.5
scaleh	1.0
Γ	3.4$\pm$0.2
χ^2/ν	86/95

ergies $\leq$1 keV. These excesses at low energies (around 0.6 and 1 keV) can be attributed to the diffuse emission from the galaxy. To account for them we had to include two `apec` models (see Caballero-García et al. 2013b for details).

For the accretion disc emission we adopted the relativistic slim disc component `SLIMULX`. This model assumes similar hypothesis to those presented by Poutanen et al. (2007), but calculating the geodesics of the photons from a slim-disc configuration consistently according to the effects of general relativity (see Sec. 2.2). In this configuration the advection and obscuration effects cause significant deviations from the X-ray spectra expected in SDT. These effects are *strongly inclination dependent and the luminosity can stay at* $\approx L_{\rm EDD}$ *even if mass accretion rate is* $\gg$1. In the case of high accretion rates the disc is strongly radiation pressure dominated and the mass of the BH can not be determined in a straightforward manner as it happens in the SDT.

Therefore we fitted the spectrum of NGC 5408 X–1 with the model `TBabs (apec + apec + slimulx + powerlaw)` in XSPEC. We used the Tuebingen-Boulder ISM absorption model (`TBabs` in XSPEC) to account for the interstellar absorption ($N_{\rm H} = 7\times10^{20}$ cm^{-2} in the direction to NGC 5408; Dickey & Lockman 1990). This parameter was set free to vary in order to account for intrinsic absorption. The distance to NGC 5408 X–1 and the spectral hardening factor κ were fixed to their canonical values, i.e. $D = 4.8$ Mpc and $\kappa = 1.5$. After some trials we found that the best values for the vertical scale of the disc and the spin of the BH were $scaleh = 1$ and $a/M = 0.99$, respectively. The best fit obtained ($\chi^2/\nu = 86/95$) gave a BH mass value of $M = 5.7\pm0.3$ M$_\odot$. We refer to Tab. 1 and Fig. 1 for the values of all the parameters found and the final fitted spectrum, respectively.

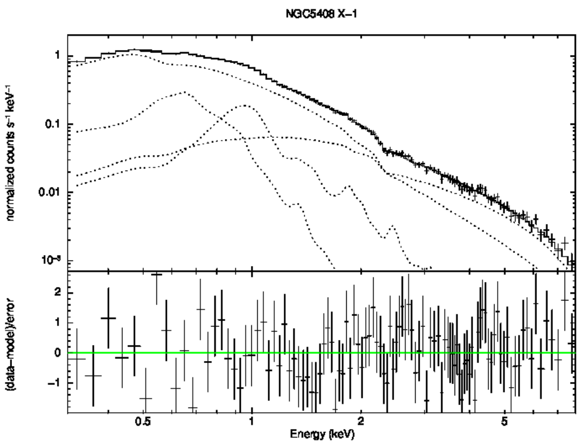

Figure 1. EPIC-pn *XMM-Newton* spectrum (top) and chi-square residuals (bottom) of NGC 5408 X–1 fitted with the spectral model shown in the text.

5. Discussion and conclusions

In this paper we briefly presented a model (`SLIMULX`) which deals with the X-ray thermal emission from a slim disc around a stellar mass BH in the super-Eddington regime. This model takes into account all the relativistic effects acting on the light in the vicinity of the BH.

We present some preliminary interesting results obtained through the analysis of the X-ray spectrum from NGC 5408 X–1 using this model. The global ($0.3 - 8$ keV) X-ray spectrum is well fitted including this model. We find that the BH is *maximally-spinning and the disc is close to face-on* ($\theta_0 \leq 26$ deg). We derive also that the system is accreting only slightly above the super-Eddington limit ($L_{\rm disc}/L_{\rm EDD} = 2.9 \pm 0.4$), giving a *mass for the BH of* $M = 5.7 \pm 0.3\,{\rm M}_{\odot}$, *thus not being an IMBH.*

The results obtained are consistent with those previously reported by Poutanen et al. (2007). They proposed that at high accretion rates an outflow forms within the so-called spherization radius (see Middleton et al. 2015 for an interpretation based on a disc-wind scenario). For a face-on observer the luminosity is high because of geometrical beaming (King et al., 2001). Such an observer has a direct view of the inner hot accretion disc, which has a peak temperature $T_{\rm max} \approx 1$ keV in stellar-mass BHs. In this model the *soft excess* corresponds to the emission from the spherization radius. Therefore, having a stellar-mass BH implies the presence of a much hotter inner accretion disc (i.e. with temperatures higher than the *soft excess*), that is observed in the spectrum if the inner disc inclination is low. Such a super-Eddington flow implies much lower values for the mass of the BH, i.e. M≈10 $M_{\odot}$, accreting at mildly super-Eddington rates ($\dot{M}/\dot{M}_{\rm EDD}$≈10).

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