Modelling multiwavelength emission of Ultra-luminous X-ray Sources accreting above the Eddington limit

E. Ambrosi, 1⋆ L. Zampieri, 2 F. Pintore 1,3 A. Wolter 4
1 INAF – IASF Palermo, Via U. La Malfa 153, 90146 Palermo, Italy;
2 INAF-Osservatorio Astronomico di Padova, vicolo dell’Osservatorio, 5, 35122 Padova, Italy;
3 INAF - IASF Milano, via E. Bassini 15, I-20133 Milano, Italy;
4 INAF, Osservatorio Astronomico di Brera, via Brera 28, 20121 Milano, Italy

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ABSTRACT

We model the multiwavelength properties of binaries accreting at super-critical rates with the aim to better understand the observational properties of Ultra-luminous X-ray Sources (ULXs). We calculate an extended grid of binary systems which evolve through Roche Lobe Overflow and undergo case A mass transfer from massive donors (up to 25 \( M_\odot \)) onto massive Black Holes (BH) (up to 100 \( M_\odot \)). Angular momentum loss with the ejection of mass through an outflow is incorporated. We apply our super-Eddington accretion model to these systems, computing their evolutionary tracks on the color-magnitude diagram (CMD) for the Johnson and HST photometric systems. We found that the tracks occupy specific positions on the CMD depending on the evolutionary stage of the donor and of the binary. Moreover, their shapes are similar, regardless the BH mass. More massive BHs lead to more luminous tracks. We additionally compute their optical-through-X-ray Spectral Energy Distribution (SED) considering the effects of a Comptonizing corona which surrounds the innermost regions of the disc. We apply our model to four ULXs: NGC4559 X-7, NGC 5204 X-1, Holmberg II X-1 and NGC 5907 ULX-2. We found that accretion onto BHs with mass in the range 35 – 55 \( M_\odot \) is consistent with to the observational properties of these sources. We finally explore and discuss the possibility to extend our model also to ULXs powered by accreting Pulsars (PULXs).

Key words: accretion, accretion discs – X-rays: binaries – X-rays: individual: NGC4559 X-7, NGC 5204 X-1, Holmberg II X-1, NGC 5907 ULX-2

1 INTRODUCTION

Ultra-luminous X-ray sources are point-like, off-nuclear X-ray sources whose bolometric luminosity exceeds the Eddington limit for a 10 \( M_\odot \) BH (\( L_{\text{Edd}} \sim 2 \times 10^{39} \text{ erg s}^{-1} \); Fabbiano 1989, see Kaaret et al. 2017 for a recent review). They have been discovered in nearby galaxies and are associated with different environments: star-forming regions or young stellar environments in spiral galaxies, or dwarf irregular galaxies (e.g. Ramsey et al. 2006, Pakull et al. 2006, Liu et al. 2007, Mineo et al. 2012). In few cases they are associated with older stellar populations in elliptical galaxies (Feng & Kaaret 2008, Roberts et al. 2008). A large number of ULXs has been found also in the young and star forming rings of ring galaxies (Wolter et al. 2018). Many of them are located in or close to young O-B associations (see e.g. the population studies performed by Soria et al. 2005; Grisé et al. 2008; Goad et al. 2002), often embedded in low metallicity environments and/or high star-forming regions (Mapelli et al. 2011; Wolter et al. 2015). Their observational properties, as the X-ray luminosity, the variability and the spectral changes indicate that the majority ULXs are likely compact objects accreting via a disc (Makishima et al. 2000; Feng & Soria 2011).

Early on, their high X-ray luminosities suggested that the mass of the compact object was higher than the average masses of the BHs observed in our Galaxy if standard accretion occurs. It was proposed (Colbert & Mushotzky 1999) that they could host Intermediate Mass Black Holes (IMBHs) with masses of \( \sim 10^3 - 10^5 \ M_\odot \). However, further investigations revealed also that their X-ray spectral properties are unusual if compared to those observed in Galactic X-ray Binaries (XRBs) (Mizuno et al. 2001) opening the possibility to explain ULXs in terms of alternative accretion disc scenarios, without invoking IMBHs. It was proposed that super-Eddington accretion discs, as the
slim discs models, around stellar-mass or slightly more massive BHs, could reproduce the spectra of ULXs (Ebisawa et al. 2003). A significant effort was devoted in recent years to understand the nature of ULXs. With the advent of more sensitive X-ray telescopes (Chandra, XMM-Newton, NuSTAR) the spectral properties of ULXs could be analyzed in greater detail. Roberts (2007), Gladstone et al. (2009) and Sutton et al. (2013b) identified the so-called Ultra luminous state, which is characterized by the presence of some important features in ULXs spectra. This led to the conclusion that ULXs should be stellar-mass or massive (up to 100 $M_\odot$) BHs accreting with marginally or highly super-Eddington rates from massive donors. In fact Belczynski et al. (2008), Mapelli et al. (2009) and Zampieri & Roberts (2009) explored the massive BH scenario, finding that low-metallicity environments could lead to the formation of BHs in the range of 30-80 $M_\odot$ and that marginal super-Eddington accretion onto these BHs could explain the observed properties of ULXs. Understanding the nature of ULXs became more and more challenging after the discovery of the first pulsating ULX (Bachetti et al. 2014), which unequivocally showed that ULXs can also be accreting neutron stars. This discovery has been confirmed by the identification of other five pulsar ULXs (Israel et al. 2017a, b; Carpano et al. 2018; Rodríguez Castillo et al. 2019; Sathiaprakash et al. 2019) whose emission properties can only be explained in terms of super-Eddington accretion (Mushtukov et al. 2017). ULXs appear to be the sources where super-Eddington accretion reveals itself in a variety of phenomenological modes. A strong evidence of such an extreme regime is also the presence of outflows, inferred from the detection of radio, optical and X-ray giant nebulae (Pakull & Mirioni 2002; Miller et al. 2005; Belfiore et al. 2020), broad optical emission lines (Fabrika et al. 2015) and blue-shifted X-ray absorption lines (e.g. Pinto et al. 2016, 2017).

The main goal of this work is to investigate the nature of ULXs using their multiwavelength emission properties along with binary evolution in the context of super-Eddington accretion.

In section 2 we present the evolutionary tracks of simulated ULX binaries with BHs and their emission properties. The third section is devoted to the comparison of our model with some nearby and well studied ULXs. Finally, in the last section we explore the possibility to extend our model to the case of PULXs.

2 EVOLUTIONARY TRACKS OF ULXS AND THEIR OPTICAL APPEARANCE

In this section we compute the evolutionary tracks of binary ULXs and their optical emission throughout it. Following previous work Belczynski et al. (2008), Patruno & Zampieri (2008) (hereafter PZ1), Mapelli et al. (2009), Zampieri & Roberts (2009) and Patruno & Zampieri (2010) (hereafter PZ2) , here we assume that these systems are High Mass X-ray Binaries, and that the compact object is a black hole which is accreting matter from a massive donor via Roche lobe overflow. We further assume that the mass transfer process starts when the donor is on the Main Sequence (case A mass transfer, see Eggleton 2006).

2.1 MESA evolutionary tracks

We used the stellar evolution code MESA (Modules for Experiments in Stellar Astrophysics, release 10108, Paxton et al. 2011, 2013, 2015), to run a set of representative ULX binaries accreting via Roche Lobe Overflow. We considered donors with masses in the range 530$M_\odot$ and BH masses in the range 10 − 100$M_\odot$. In this work the donor metallicity is fixed at the solar value (Y = 0.28, Z= 0.02). However, we tested the validity of this approximation and evolved some binaries with sub-solar metallicity. The resulting tracks (see App. A) show that this is a valid approximation for the scope of this work. We also underline that Klencki et al. (2020) studied the effects of metallicity on binary evolution, and found that it plays an important role only for those systems which start the accretion phase when the donor is an evolved star (case B mass transfer). As we focus our analysis on systems that start mass transfer on the main sequence (case A mass transfer), in the following we consider the assumption of solar metallicity acceptable. We took into account the effects of the wind mass loss, which affects significantly the evolution of massive donors. Among the wind schemes that can be implemented, we chose the method that in MESA is called ‘Dutch wind scheme’, which differentiates the wind mass loss prescription for the stars in the Main Sequence (MS) from that after the main sequence, following the work by Giebbeck et al. (2009). For the MS we used the default input relation (Vink et al. 2001, 2000). For the evolved stars we adopted the de Jager relation (de Jager et al. 1988) that, as observed by Renzo et al. (2017), is useful when the main objective is to study mass loss along the evolution on the HR diagram. We also note that in the specific systems we made evolving, i.e. during RLOF, mass loss via accretion is orders of magnitude higher than that expelled through stellar wind (see also Smith 2014 for a comprehensive review), so that we do not expect that a different wind prescription can considerably alter our results.

First, we run the star module for each donor mass. Then, we set the start of the RLOF phase during Main Sequence (MS), when the central Hydrogen abundance (h1) is $\approx 0.5$ (case A mass transfer). We denote the radius of the donor at this stage with $R = R_{d,h1}$. The evolution is stopped at the onset of helium burning in the core. We set the initial period for the binaries combining Kepler’s law:

$$P \approx 2\pi G^{-1/2} \frac{a_1^{3/2}}{a_1^{3/2} + (M_d + M_a)^{-1/2}} \quad (1)$$

with the Eggleton approximation. Under the hypothesis that $R_{d,h1} = R_L$ (Eggleton 1983):

$$a_1 \approx \frac{R_{d,h1}}{0.49q^{2/3}} \left[ 0.6q^{2/3} + \ln(1 + q^{1/3}) \right] \quad (2)$$

where $R_L$ is the Roche Lobe Radius of the donor, $a_1$ is the initial orbital separation, $M_d$ and $M_a$ are the donor and accretor mass, and $q = M_a/M_d$. The initial orbital periods turn out to be in the range 1-2 days. The RLOF is calculated with the MESA implicit scheme ‘Roche Lobe’. We set the minimum mass transfer rate at $M_{\text{min}} = 1.0 \times 10^{-12} M_\odot/\text{yr}$. The timestep is chosen in such a way to have an adequate time resolution without excessively increasing the computational time (typically about $\approx 4 - 5$ hours). As the binary evolution proceeds faster after the Terminal Age Main Sequence (TAMS), the time resolution for the evolution of the
donor during the post-MS stages is tighter than that adopted during the MS. We also set to zero the initial spin of the BH, which increases as accretion proceeds.

2.1.1 Orbital angular momentum through the outflow

According to the model with an accretion disc plus an outflow adopted in Ambrosi & Zampieri (2018), hereafter AZ, the evolution proceeds via non-conservative mass transfer and the accretion flow is not Eddington-limited. When the mass transfer rate becomes super-critical, the mass ejected with the outflow effectively removes also orbital angular momentum. The total outflow rate depends on the fraction of radiative energy spent in launching the wind, $\epsilon_w$, and is given by (eq. 24 of Poutanen et al. 2007):

$$M_w \approx a_w \dot{M}$$

where $\dot{M}$ is the mass transfer rate and, following Poutanen et al. 2007, $a_w = \epsilon_w (0.83 - 0.25 \epsilon_w)$. We assume that half of the radiative energy accelerates the outflow ($\epsilon_w = 0.5$) and then $a_w = 0.3525$.

As the outflow is launched from the inner disc where the radiation pressure is higher, we assume that matter leaves the system from the vicinity of the BH. The resulting orbital angular momentum loss is implemented in MESA following Soberman et al. (1997):

$$\dot{J}_{orb} = \alpha + 3 q^2 + \delta (1 + q)^2 \frac{M_d}{1 + q}$$

where $\alpha$ is the fraction of the mass lost from the donor, $\beta$ that expelled from the zones near the accretor, and $\delta$ that expelled from a circumbinary planar toroid with radius $r_1 = \gamma^2 a$ (we refer to van den Heuvel 1994 and Paxton et al. 2015 for details). According to Eqs. 4 and \(3\), we then set $\beta = a_w = 0.3525$, $\alpha = \delta = \gamma = 0$.

2.1.2 Evolutionary tracks

The evolution of the mass transfer rate for the systems considered here is shown in Fig. 1. The tracks are grouped together according to the initial BH mass and color-coded according to the initial donor mass. We describe the evolution of the tracks taking as reference the systems accreting onto a 10$M_\odot$ BH. They span a wide range in the mass ratio $q$, which is an important parameter driving the evolution of accreting binaries (see Eggleton 2011). We distinguish three different evolutionary paths.

For very massive donors of 25 and 30 $M_\odot$ ($q = 2.5$ and $q = 3$ respectively), the accretion phase starts abruptly with an instability, reaching high rates (up to $10^{-1} - 1$ $M_\odot$/yr, see top left panel of Fig. 1). The timescale for mass transfer ($\tau_M = M/\dot{M}$) is faster than the thermal timescale, as shown in the top left panel of Fig. 2: $\tau_{KH} H^2$ is up to six orders of magnitude larger than $\tau_M$. Moreover, as the donor loses mass, it is driven rapidly towards instability, being the mass transfer rate higher than the maximum value permitted by the condition of hydrostatic equilibrium (see Pols 2011 and the second and third left panels of Fig. 2). This effect is likely to lead the system towards a common envelope (CE) phase. This particular phase of binary evolution needs a dedicated modelling with physical assumptions different from those adopted for RLOF accretion, which is the relevant mechanism considered here for persistent ULXs.

For this reason we stop the evolution of these systems at this stage, and postpone the inclusion of the CE phase in our model to a future paper.

Donors with initial mass of 15 and 20 $M_\odot$ ($q = 1.5$ and $q = 2$ respectively) go through the first, thermal unstable mass transfer episode but do not become dynamically unstable: $\tau_M$ is shorter than $\tau_{KH}$ (top left panel of Fig. 2) but the ratio between the dynamical timescale and the mass transfer timescale decreases driving the system towards stability (middle left panel of Fig. 2). As they lose mass, and the BH grows, the mass ratio decreases, the system detaches and the donor restores the thermal equilibrium. Therefore, the evolution is stable and proceeds on the nuclear timescale.

We emphasize the extreme properties of the track of the 20 $M_\odot$ donor: after having lost more than 50% of its mass during the first fast episode, the system widens and detaches. The donor restarts RLOF at about TAMS.

For lower donor masses with $q \leq 1$ the evolution does not go through the first unstable phase of mass transfer, but it proceeds smoothly up to the TAMS, being the mass transfer timescale longer than both the Kelvin-Helmholtz and dynamical timescales. Accretion during the giant phase proceeds with high accretion rates, but the donors maintain both hydrostatic and thermal equilibrium.

The evolution of systems accreting onto more massive BHs proceeds in a similar way but the initial accretion episode is less extreme for the more massive donors. For the 20$M_\odot$ BH, the 25 $M_\odot$ and 30 $M_\odot$ donors can restore thermal and dynamical equilibrium, at variance with the 10 $M_\odot$ case. For the 50 $M_\odot$ BH the evolution is always stable (right panels of Fig. 2). Accretion is super-Eddington only during the giant phase.

Figs. 3a-3f show the evolution of a few chosen parameters of the binary systems: donor and BH mass (upper and lower left panels), orbital period and mass ratios (upper and lower right panels of each figure). The 5 $M_\odot$ donor is almost totally stripped irrespectively of the BH mass (see dashed dark blue lines in the upper left panels). Being its mass almost totally stripped, MESA could not find a convergent solution during the final phases and then its evolution was stopped before the onset of He burning in the nucleus. From Figs. 3a-3f we see that irrespectively of the BH mass, the final orbital period is shorter for systems with more massive donors. For a given BH mass, the final orbital period for 8$M_\odot$ donors can be one order of magnitude longer than that of a 30 $M_\odot$ donor. Finally, we emphasize that the accretion process changes dramatically the masses of the binary components. Donors lose more than 50% of their initial mass, as shown in the upper left panels of Fig. Figs. 3a-3f. BHs acquire $\sim 2 M_\odot$ from 5 $M_\odot$ donors (dark blue lines in Figs. 3a-3f) and $\sim 10 M_\odot$ from 30 $M_\odot$ donors (dark red lines in Figs. 3b-3f).
Figure 1. Evolution of the mass transfer rate for the binaries analyzed in this work. The BH mass is fixed in each panel. Short dashed lines refer to donors of 5 (dark blue), 8 (blue) and 10 (light blue) $M_\odot$, solid lines to donors of 12 (azure) $M_\odot$, dashed double-dotted lines to donors of 15 (salmon) $M_\odot$, and long dashed lines to more massive donors of 20 (orange), 25 (red) and 30 (dark red) $M_\odot$. 

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Figure 2. Evolution of the characteristic timescales for binaries accreting onto 10 (left) and 50 (right) $M_\odot$ BHs. Upper panel: evolution of the ratio between the Kelvin-Helmholtz ($\tau_{KH}$) timescale of the donor and the characteristic timescale for the mass transfer $\tau_m$. Middle panel: evolution of the ratio between the dynamical timescale $\tau_{dyn}$ of the donor and the mass transfer timescale. Lower panel: evolution of the maximum value of mass transfer achievable without perturbing the hydrostatic equilibrium of the donor.

2.2 Optical emission of ULXs

2.2.1 Effects of super-Eddington accretion on optical emission

To determine the emission properties of accreting ULXs, we applied the model described in AZ to the evolutionary tracks of the systems reported in the previous section. The model computes the optical emission in the UBVRI Johnson and in the HST WFPC2, ACS and WFC3 photometric systems, that can be used to make a detailed comparison with the observed optical counterparts of ULXs. The optical emission of accreting binary systems is produced by different components, each contributing with a different weight to the total optical emitted flux, depending on the accretion regime and evolutionary stage. These components are:

- the donor star, the properties of which are different from that of an isolated star with the same initial mass (see Copperwheat et al. 2005, PZ1, PZ2, Eggleton 2011; Pols 2011 for details): during RLOF, its radius is constrained to be the Roche lobe radius and its temperature is determined by the condition of thermal equilibrium. Moreover, it can be heated up by the X-ray flux produced by the disc;
- the outer portion of the accretion disc that, for both sub-Eddington and super-Eddington accretion, is a standard Shakura & Sunyaev disc, and emits an optical flux proportional to the mass transfer rate. This region can reprocess and thermalize the X-rays from the innermost regions (see PZ1, PZ2, AZ and references therein);
- the outflow, the radial extension of which depends on the mass transfer rate. For extremely super-Eddington accretion, the outflow produces a large amount of optical radiation, which can significantly contribute to the total luminosity and, in the more extreme regimes, be the dominant component (see AZ).

As mentioned above, a strong contribution to the optical emission comes from the reprocessing of the X-ray-UV radiation produced by the inner regions of the disc and impinging in the outer disc and the donor star. If the disc is accreting at sub-Eddington rates, the flux intercepting
Figure 3. Evolution of the parameters for the binary systems evolved with MESA: donor mass (upper left), orbital period (upper right), BH mass (lower left), and q ratio (lower right). Systems are grouped according to the BH mass and color-coded according to the donor mass as in Figs. 1 and 2.
the outer disc and the donor star makes the latter bluer than an isolated star with the same mass (see e.g. PZ1) and produces a bump in the red tail of the disc optical spectrum (see e.g. Sanbiuchi et al. 1993).

Self-irradiation for super-Eddington accretion is more complex. In AZ we showed that the innermost regions of the disc do not irradiate the outer ones, because of the intervening outflow. The X-ray-UV irradiating flux is produced by a region located outside the outflow, the extension of which depends on the mass transfer. In addition, for extremely super-critical mass transfer rates, the region outside the optically thick photosphere of the outflow (details can be found in AZ). From top to bottom, the BH mass increases from 10 $M_\odot$ to 100 $M_\odot$.

The evolutionary tracks of ULXs occupy two regions on the CMD, depending on the evolutionary stage of the donor. When the donor is on the MS and accretion is sub-critical or marginally super-critical, the tracks are blue and their $M_V$ magnitude is limited to $\sim -6$. They occupy the bluer and comparatively fainter corner of the CMD, and are represented by the light-pink coloured lines in Fig. 5. We notice that they are similar in shape for different BH masses, the main difference being the maximum value of $M_\dot{\nu}$: more massive BHs generate more luminous tracks.

When the donor ascends towards the giant branch, the properties of the evolutionary tracks are governed by the mass transfer rate, which is now super critical, as shown in Fig. 1. Moreover, the binary separation increases rapidly producing a more extended accretion disc, which emits a huge optical flux enhanced by self-irradiation. This evolution drives the tracks towards higher $V$ band luminosities. The colors are initially blue because the mass transfer rate at the beginning of the giant phase is very high and the disc is hot. As the super-Eddington mass transfer continues, the systems widen and the accretion disc becomes more extended, driving the tracks towards redder colors. In addition, self-irradiation is essentially suppressed. However, after the peak, the mass transfer rate starts to decrease, irradiation starts to contribute again to the optical flux and for systems with more massive donors the evolution towards the red slows down. These super-critical evolutionary stages are reproduced with the dark pink lines in Fig. 5. We notice that the track of the 5 $M_\odot$ donor differs from the others. We will describe this case and the behaviour of the tracks for the various BH masses in Appendix B.

3 MULTIWAVELENGTH SED OF NEARBY ULXS

In AZ we concluded that the emission of the disc plus outflow alone cannot fully reproduce the observed data, because the X-ray spectrum at the highest energies is too soft and cannot properly describe the ULXs spectra. In many ULXs observations show evidence of a spectral component that can be interpreted as an optically thick and cool corona covering the innermost regions of the disc (e.g. Gladstone et al. 2009, Pintore & Zampieri 2012, Sutton et al. 2013b). Thus, we added the contribution of a comptonizing corona, which covers the innermost regions of the disc, to the emission model of AZ.

3.1 Comptonization from an optically thick corona

We approximate the corona with a sphere of radius $r_c$ which extends up to the radius where the outflow becomes optically
where \( r_{ph,in} \) is the inner photospheric radius of the outflow (see AZ). Following the observational evidence gathered from the X-ray spectral analysis (e.g. Pintore & Zampieri 2012, Pintore et al. 2014), we assume that the Compton parameter in the corona is significantly larger than unity and that Comptonization is saturated. In these assumptions, the high energy tail of the specific intensity of the source can be approximated with a Wien distribution (Rybicki & Lightman 1986):

\[
I_{\nu}^W = \frac{2h\nu^3}{e^2} e^{-\alpha} e^{-h\nu/kT_e},
\]

(6)

where \( T_e \) is the electron temperature of the corona. Since Compton scattering conserves the photon number, the value of the factor \( e^{-\alpha} \) is determined from the relation:

\[
N_{ph}^W = N_{ph}^d.
\]

(7)

Here, \( N_{ph}^d \) is the number of photons per unit time emitted from the disc which, for an observer at distance D, takes the
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Figure 6. Evolutionary tracks on the color-magnitude diagram of the synthetic binary systems evolved with MESA: $M_I$ vs V-I color.

form:

$$N_{ph}^d = \pi \int_0^{r_{in}} \int_{r_{ph,in}} \left( \frac{I_d^d}{\hbar \nu} \right) \frac{2\pi D^2}{(r^2 + D^2)^2} dr d\nu,$$

while

$$N_{ph}^W = \pi \frac{r_v^2}{r_v^2 + D^2} \int_0^{\infty} \frac{I_W^W}{\hbar \nu} d\nu$$

is the number of photons which is emitted per unit time from the corona and $r_{in}$ is the inner disc radius. In the following, we consider two reference electron temperatures for the corona: 1.2 and 1.5 keV. These temperatures sample the typical range of temperatures inferred from modelling the observed ULXs spectra (Pintore et al. 2014).

3.2 Model-data comparison

This section is dedicated to the comparison of our model with the optical and X-ray data of a few nearby ULXs. We constrain the model parameters using the photometric data and X-ray spectra of the sources. With the addition of an optically thick Comptonizing corona, our model can reproduce the Multiwavelength emission of ULXs in an acceptable way, and can be effectively used to constrain the properties.
We follow Soria et al. (2005) and Tao et al. (2011) and as-

3.2.1 NGC 4559 X-7

belong is known, and we will use it as a further constraint

the population to which NGC 4559 X-7 and Holmberg II X-

with HST data, c) the ULXs have high X-ray luminosity.

c) the compact object is unknown, b) the optical emi-

tion of a ULX on the CMD. We search for in-

Search for the best fit of the multiwavelength SED:

Comparison with the CMD diagram: the first step is to

search the synthetic evolutionary tracks that intersect the
the optical emission of a ULX on the CMD. We search for in-

optical thicknesses, when possible, in more than two colors, which

provides an additional constraint.

2. Age selection: the comparison with the evolutionary

tracks typically produces several intersections. Therefore we

select the model using an additional constraint, which is the

age of the ULX inferred from the population study on the

host environment.

3. Search for the best fit of the multiwavelength SED:

finally, after having selected the intersections matching the age

of th ULXs, we computed the synthetic optical-through-X-ray

SED of the correspondent snapshot of the track considering
two electron temperatures of the optically thick corona:

kT_e = 1.2 and 1.5 keV. The most representative SED is

chosen applying a chi-square test to the data-model com-

parison. Although we remark that we are not adopting a
data spectral fit, the chi-square test empowers the selection

process.

We applied our model to those ULXs that satisfy some spec-
cific criteria: a) the compact object is unknown, b) the optical

counterpart has been univocally detected and analyzed with HST data, c) the ULXs have high X-ray luminosity.

These sources are NGC 4559 X-7, NGC 5204 X-1, Holm-

berg II X-1 and NGC 5907 ULX-2. In addition, the age of the

population to which NGC 4559 X-7 and Holmberg II X-

1 belong is known, and we will use it as a further constraint

to the model selection.

3.2.1 NGC 4559 X-7

We follow Soria et al. (2005) and Tao et al. (2011) and as-

sume a Galactic extinction E(B−V) = 0.018 and a distance of

10 Mpc ᵃ of the host galaxy. We consider the average of the

magnitudes and colors taken from two measurements (Tao et al. 2011): F555W = −7.65 ± 0.08 and F555W-F814W = −0.11 ± 0.13. We take as reference age for this source the age of the parent population: ~ 20 Myr (Soria et al. 2005). The position of the source on the CMD intersects the tracks of donors with initial mass of 15 M☉ accreting onto a 50 and 70 M☉ BH during the shell H-burning phase and tracks of evolved donors with initial mass of 12, 15 and 20 M☉ accreting onto a 100 M☉ BH. The age of all tracks of X-7 at intersection (~ 15 Myr) are in agreement with that esti-

mated from its stellar environment (~ 20 Myrs, Soria et al. 2005). We then fitted their multiband SEDs to further con-

strain the models. We consider the XMM-Newton and NuSTAR observations of June 2019 (see Tab. 3.2). Indeed, the intersection of the ULX photometric point with a certain evolutionary track covers hundreds or thousands of years and fixes the average mass transfer rate at the Lagrangian point. The short term fluctuations of the accretion rate and physical conditions in the system must be averaged out when performing this comparison. Therefore, the error bar of the X-ray spectrum encompasses the daily/monthly/yearly variability range of the source flux that is typically a factor of ~2. Table 2 shows the best fitting evolutionary tracks based on the χ² statistics: X-7 is reproduced with a system having donor of actual mass in the range 5-6 M☉ accreting onto a massive BH with actual mass of ~ 56 M☉. Accretion onto a 70 and 100 M☉ BH are excluded by the spectral fitting. The SED fit and the observed X-ray luminosity of X-7 (~ 2 × 10³⁰ erg s⁻¹ Soria et al. 2005) are better in agreement with a low corona temperature (Tab. 2). X-7 is well reproduced with a system accreting at largely super-critical rates onto a massive BH from donors which are ascending along the Giant Branch. Having lost most of their mass during the MS, are now less massive, with masses in the range 5-6 M☉. The orbital period of this systems is quite long (> 12 days, see Tab. 2) because the donor is evolved and has lost a large amount of mass. Fig. 7 shows that at these stages of the evolution, the optical emission is dominated by the outer accretion disc, which reaches a very high optical luminosity because of the high value of the mass transfer rate (dashed black line). At the same time, the very extended outflow dominates the UV/soft X-ray emission.

3.2.2 NGC 5204 X-1

NGC 5204 X-1 is located in the spiral galaxy NGC 5204 and has an average X-ray luminosity of 3 × 10³⁹ erg s⁻¹. It is found to vary by ~ 50% in 10 years (Liu et al. 2004). The source is thought to reside in a young stellar cluster with age < 10 Myr (Goad et al. 2002). Among the data collected by Tao et al. (2011), we will consider the averages of those taken in August 2008: F555W = −5.646 ± 0.055 and F450W = −5.848 ± 0.027 adopting a distance of 4.3 Mpc and galac-
tic extinction E(B−V) = 0.013. The optical counterpart of NGC 5204 X-1 is intersected by: the tracks of donors with initial mass of 20 and 25 M☉ accreting onto a 20 M☉ BH at super-critical rates while the donor is ascending the Giant Branch; the track of a 20 M☉ donor accreting onto a 30 M☉ BH in the first stages of its H-shell burning phase, or the track of a donor with initial mass of 30 M☉ near the TAMS; the tracks of donors with initial mass 25 and 30 M☉ accreting onto BHs of 50, 70 and 100 M☉ during Main Sequence. These three cases differ in the evolutionary stages at which they occur: the more massive is the BH, the younger is the age of the system for the same initial donor mass, as we discussed in the previous section. However, constraining the tracks with the age of the parent population does not help much, because the intersections are with tracks of very massive donors, whose evolution is very fast. We could rule out only the tracks of donors with initial

Table 1. Log of the X-ray observations used in this work.

| ULX    | Instrument       | Obs.ID        | Date       | Exp. (ks) |
|--------|------------------|---------------|------------|-----------|
| NGC 4559 X-1 | XMM-Newton   | 0642100201   | 2013-06-16 | 74.3      |
|         | NuSTAR          | 30501004002   | 2019-06-17 | 94.9      |
| NGC 5204 X-1 | XMM-Newton   | 0605851901   | 2014-04-21 | 16.9      |
| Hol II X-1     | XMM-Newton   | 0200470101   | 2004-04-15 | 10.0      |
|         | NuSTAR          | 30000103002   | 2011-06-29 | 31.4      |
|         | NuSTAR          | 30000103063   | 2014-09-09 | 79.4      |
| NGC 5907 X-2   | XMM-Newton   | 0759712601   | 2017-12-01 | 68.8      |

\( M_\odot \)
mass of 25 $M_\odot$ which accrete onto BHs of 20 and 30 $M_\odot$. We then calculated the fit for the sources analyzed in this work. 

We calculated the SED for all the other intersections and searched for the models that best fit our data, using only the X-ray spectrum of Liu et al. (2004) (see Tab. 3.2) and assuming an X-ray flux variability of 50\%.

Running through all the SEDs selected according to photometry and age, with the two aforementioned electron temperatures of the corona, leads us to exclude the majority of the models. The system which better reproduces the optical and X-ray data is the one with initial donor and BH mass of 30 $M_\odot$, with actual donor mass of about 13 $M_\odot$ and present BH mass of about 40 $M_\odot$ which undergoes marginal super-Eddington accretion during TAMS.

However, the fit is formally not statistically acceptable and the bolometric luminosity is not well reproduced. The reason for which the fit is not satisfactory is related to the fact that the last two points of the X-ray spectrum are not well reproduced. The source is harder than what predicted by our model and seems to require an additional component to fit the X-ray data points at the highest energies, as noted by Mukherjee et al. (2015).

### 3.2.3 Holmberg II X-1

Holmberg II X-1 is located in the dwarf irregular galaxy, Holmberg II, which is in the M81 group of galaxies at a distance of 3.05 Mpc (see Tao et al. 2011, 2012 and references therein). Its luminosity reaches $\sim 3 \times 10^{40}$ erg s$^{-1}$ (Grisé et al. 2010). The source is surrounded by a photoionized optical nebula (Kaares et al. 2004) containing a point-like optical counterpart. A study published by Egorov et al. (2017) shows that X-1 is escaping from a very young cluster aged $\sim 3.5 - 4.5$ Myrs (Stewart et al. 2000), which will be the reference age for our study. We take the photometry from Tao et al. (2012), that reported the average fluxes of non simultaneous observations in the F814W, F555W, F450W and F336W filters: $(2.71 \pm 0.54) \times 10^{-18}$, $(7.74 \pm 1.55) \times 10^{-18}$, $(1.34 \pm 0.27) \times 10^{-17}$ and $(2.70 \pm 0.54) \times 10^{-17}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, respectively. We search for intersections of the evolutionary tracks with data points on the CMD (calculated for different filters). Note that, because of the significant optical variability of the source, the error bar on the color is large and the intersections of the datapoint with

### Table 2

Best fit models found minimizing the $\chi^2$ for the sources analyzed in this work.

| System          | $M_\text{BH,i}$ | $M_{\text{d,i}}$ | $L_{\text{bol,i}}$ | $t$ (Myr) | $P$ (d) | $\chi^2$ | d.o.f. |
|------------------|----------------|-----------------|-------------------|-----------|---------|---------|--------|
| NGC 4559 X-7     | 50 $M_\odot$   | 30 $M_\odot$    | 3.2 $10^{40}$     | 12        | 6.8     | 39      | 6.4    | 5.5 | 8.20 $\times 10^{39}$ | 106.4 | 21  |
| NGC 5204 X-1     | 50 $M_\odot$   | 30 $M_\odot$    | 3.2 $10^{40}$     | 12        | 6.8     | 39      | 6.4    | 5.5 | 8.20 $\times 10^{39}$ | 106.4 | 21  |
| Holmberg II X-1  | 50 $M_\odot$   | 30 $M_\odot$    | 3.2 $10^{40}$     | 12        | 6.8     | 39      | 6.4    | 5.5 | 8.20 $\times 10^{39}$ | 106.4 | 21  |
| NGC 5807 ULX-2   | 50 $M_\odot$   | 30 $M_\odot$    | 3.2 $10^{40}$     | 12        | 6.8     | 39      | 6.4    | 5.5 | 8.20 $\times 10^{39}$ | 106.4 | 21  |

Figure 7. Left: intersection of the optical counterpart of NGC 4559 X-7 (green point) with the evolutionary tracks of a 50 $M_\odot$ BH. Right: total SED for the best fit solution together with the single spectral components. The total SED has the same color of the evolutionary track (see left panel) to which it belongs. Green and lightgreen points indicates optical and X-ray data, respectively.
the simulated evolutionary tracks are numerous. Considering the very young age inferred by Stewart et al. (2000), the majority of the intersections are ruled out and we are left with systems accreting onto massive BHs (50 and 70 $M_\odot$) from donors with initial mass from 15 to 25 $M_\odot$. We then compared the SEDs obtained with our model with the observed optical through X-ray SED of Holmberg II X-1. The X-ray data are taken from Pintore et al. (2014) (see Tab. 3.2). Given the very young age, the majority of the best fitting SEDs belong to systems in the sub-Eddington accretion phase, which can reproduce well the softer part of the X-ray spectrum but have a significantly different Spectral Energy Distribution at the higher frequencies. The intersection that best fits the data is a system with a main sequence donor younger than 10 Myrs with initial mass of 20 $M_\odot$ accreting onto a BH with initial mass of 50 $M_\odot$. The system is accreting marginally above Eddington ($\dot{M} \sim 10$). The actual mass of the donor is about 11 $M_\odot$ and that of the BH about 55 $M_\odot$. The orbital period is short ($P \sim 5.5$ d), because during the long and stable MS RLOF phase, the mass ratio of the system does not change dramatically (see Tab. 2). Fig. 9 shows that the SED that best fits the data is produced by a cool corona with an electron temperature of 1.2 keV. Moreover, being the accretion rate marginally super-critical, the outflow is not very extended and does not contribute much to the X-ray emission. Looking at the optical emission, it is dominated by the donor star but also the standard disc contributes in a significant way.

3.2.4 NGC 5907 ULX2

NGC 5907 ULX2 (Pintore et al. 2018) is located at a distance of 17.1 Mpc and it reached a peak X-ray luminosity of $6.4 \times 10^{39}$ erg s$^{-1}$. Being a recent discovery, it is not well studied, and we do not have much information on its variability during the active phase. However, we know that the source is transient because in a previous observation taken in 2012, Chandra did not detect it (with an upper limit of $1.5 \times 10^{39}$ erg s$^{-1}$ on the X-ray luminosity). Clearly, our model does not take into account the disc instabilities that may lead to a transient behaviour. However, we can use it to approximately describe its active phase. We used the optical photometry and X-ray data presented in Pintore et al. (2018) (see see Tab. 3.2). Some of the synthetic tracks intersect with the photometric point of NGC 5907 ULX-2 on the CMD computed using the F450W magnitude and F450W-F814W color. The source cannot be reproduced by systems accreting onto a 10 or 20 $M_\odot$ BH. On the basis of the photometry the system can be a BH of 30 $M_\odot$ accreting from a donor which has an initial mass of 15 $M_\odot$, 50 $M_\odot$ from a donor with initial mass of 15 $M_\odot$, 70 $M_\odot$ from donors with initial mass of 12 and 20 $M_\odot$ and 100 $M_\odot$ from a donor with initial mass of 12 and 15 $M_\odot$.

For this source we did not find information on the age of the host environment. Therefore in the following we considered all the snapshots that intersect the photometric point. Tab. 2 shows the result of the $\chi^2$ test applied to the snapshots run for this source. The observed multiwavelength SED is better reproduced with a system composed of a donor star with mass of about 5.4 $M_\odot$ which is accreting at super-Eddington rates onto a BH of about 36 $M_\odot$. The system initially consisted of a 15 $M_\odot$ donor and a 30 $M_\odot$ BH. The accretion phase takes place while the donor is ascending along the Giant Branch. The binary has an orbital period of $\sim 24$ d, therefore the disc is very extended. In Fig. 10 we show the different components which contribute to the overall emission spectrum: the optical band is dominated by the outer accretion disc, which is very bright because of the very high mass transfer rate.

4 UNVEILING ULX PULSARS FROM OPTICAL DATA: AN EXPLORATORY STUDY

Since the discovery of the first pulsating ULX in 2014 (Bachetti et al. 2014) five other sources have been found to be accreting pulsars (Israel et al. 2017a,b; Carpano et al. [2018]). Some of these sources (NGC 7793 (Bachetti et al. 2014) and NGC 5907 ULX-2 (Pintore et al. 2018)) have been studied in the optical since their discovery, and we could therefore use the optical photometry to deduce the donor mass and hence check if they are in the range of the expected mass for the pulsars. Our model predictions are in agreement with these results, and therefore we can use it to predict the donor mass for other sources.

The method developed here is therefore quite general and can be applied to any source with a known optical counterpart and X-ray flux. This will allow us to study more sources and to constrain the properties of the donor stars, which are key to understanding the nature of these systems.
2018; Sathyaprakash et al. 2019; Rodriguez Castillo et al. 2019). Detecting pulsations likely requires a specific viewing angle and/or special physical conditions. If pulsars are not detected, it would be useful to have alternative approaches to distinguish between ULXs accreting onto a BH or a NS. In Pintore et al. (2017) a large sample of bright ULXs have been studied with the aim to search for specific signatures in the X-ray spectra that could be linked to the nature of the compact object. Above 2 keV, the spectra of the known ULX pulsars are harder than those of other ULXs analyzed in their study. However, despite the effort, a clear spectral signature has not been found so far. Modelling the evolution and multiwavelength emission properties of ULX binary systems represents, in principle, an additional tool to assess the nature of the compact object and, at the same time, to understand the evolutionary paths that can lead to the formation of these systems (see PZ1, PZ2 and AZ). A detailed investigation of pulsars ULXs is beyond the scope of the present paper. Here we present only a preliminary study of the optical emission properties of ULX binary systems with a neutron star, that undergo a transient (quasi-steady) RLOF accretion phase similar to that of massive donors in BH binaries. The purpose of the present investigation is simply to study the evolution of quite stable, low donor mass NS ULXs to get a grasp of their possible evolutionary paths and emission properties. High donor mass non-conservative systems are well beyond the present goals. Of course, the results presented here will not be relevant or applicable if all NS ULX binaries will definitely turn out to be system of the latter type.
4.1 Optical Emission of Pulsar ULXs

We used the evolutionary code MESA (Paxton et al. 2011, 2015) to evolve binaries with different masses accreting onto a neutron star. In this first exploratory study we did not consider the magnetic field of the neutron star, because we are only interested in the optical emission that originates in the outer region. Moreover, we simplify the problem considering that the mass transfer is conservative, since non-conservative mass transfer onto NS from a massive donor is beyond the scope of this paper. Here, we show how the optical emission evolves under the following assumptions:

- a non-magnetized NS of 1.4 $M_\odot$;
- conservative mass transfer;
- case A mass transfer until the NS becomes very massive (we choose an upper limit of 2.5 $M_\odot$) or mass transfer becomes unstable;
- donor stars with masses in the range 2-4 $M_\odot$.

This range of mass is broadly consistent with the donor of NGC 5907 ULX-1, which is thought to be an intermediate mass star in the range 2-6 $M_\odot$ (Israel et al. 2017a); although the extinction in the direction of the source is very high (Heida et al. 2019). In addition, this assumption is also approximately consistent with the non-detection of the counterpart of M82 X-2, if its donor belongs to the lower end of the range obtained by Bachetti et al. 2014: $M_d \geq 5.2 M_\odot$. More massive donors cannot steadily be evolved with this model. Given the low mass of the neutron star, we found that systems with donors more massive than 4 $M_\odot$ started abruptly dynamic unstable mass transfer. We show the evolution of two representative systems with an intermediate donor mass and a quite different $q$ ratio.

**Systems with donor of 2.5 $M_\odot$**

When the RLOF phase of this system starts, accretion is super-Eddington, as it can be seen from the upper left panel of Fig. 11. The system initially shrinks (upper-right panel of Fig. 11), then it starts to expand while the mass transfer decreases. After $\sim 4$ Myr from the onset of RLOF the neutron star mass reaches the critical value of 2.5 $M_\odot$ and the evolution is stopped.

**Systems with donors of 4 $M_\odot$**

The system with a 4 $M_\odot$ donor starts accretion with a higher mass transfer rate than the previous case. During the short-lived RLOF phase ($\approx 7.0 \times 10^4$ yr) the system shrinks and the donor becomes unstable after having lost most of its mass.

**Evolutionary tracks on the CMD**

The evolutionary tracks on the CMD of the two binary pulsar ULXs described above are shown in Fig. 12, where the colormap represents the magnitude of the mass transfer rate normalized to the Eddington limit of the evolving Neutron Star.

Both tracks have blue colors but the V band magnitude is very faint and considerably weaker than that of the evolutionary tracks of BH ULXs. The optical counterparts of ULX

![Figure 11](image-url)  
**Figure 11.** Upper panel: evolution of the mass transfer rate (left) and the orbital period (right) for a system with a 2.5 $M_\odot$ donor and a 1.4 $M_\odot$ neutron star. Lower panel: the same for a system with a 4.0 $M_\odot$ donor. The mass transfer is super-critical at the onset of RLOF being the Eddington limit for a neutron star $L_{\text{Edd,NS}} \approx 10^{-8} M_\odot /\text{yrs}$

![Figure 12](image-url)  
**Figure 12.** Colour-magnitude diagram in the $B - V$ colour and $M_V$ magnitude for systems with donors of 2.5 (lower line) and 4 (upper line) $M_\odot$ accreting onto a NS with initial mass of 1.4 $M_\odot$. The colormap represents the mass transfer rate normalized to the Eddington limit. The arrows indicate the direction of the evolution.
pulsars are essentially undetectable with HST if the masses of the donor stars are in the range 2.5-4 $M_{\odot}$. This result is consistent with the non-detection of the counterpart of NGC 5907 ULX-1 (Sutton et al. 2013a; Heida et al. 2019). However, systems like NGC 7793 P13 that have a massive companion of 18-21 $M_{\odot}$ in an eccentric orbit (Israel et al. 2017b; Hu et al. 2017) can not clearly be reproduced by a transient accretion phase of the type considered here.

5 SUMMARY AND CONCLUSIONS

We calculated an extended grid of evolutionary tracks of ULX binary systems with the MESA code. We considered a wide range of BH masses (10-100 $M_{\odot}$) and donor masses (5-30 $M_{\odot}$) and properly incorporated the orbital angular momentum loss in case of super-Eddington accretion with an outflow. For the calculation of the tracks we adopted the model described in AZ. We found that they occupy two regions on the CMD, depending on the evolutionary stage of the donor.

When the donor is on the MS and accretion is sub-critical or marginally super-critical, the tracks are blue and their $M_V$ magnitude is limited to $\sim -6$. They occupy the bluer and comparatively fainter corner of the CMD. We noticed that they are similar in shape for different BH masses, being the main difference the maximum value of $M_V$: more massive BHs generate more luminous tracks.

When the donor is ascending towards the Giant Branch, the properties of the evolutionary tracks are governed by the mass transfer rate, which is now super critical. Moreover, the binary separation increases rapidly producing a more extended accretion disc, which emits a huge amount of flux in the optical band, that can be enhanced by self-irradiation. This evolution drives the tracks towards redder V band luminosities. The colors are initially blue because the mass transfer rate at the beginning of the Giant phase is very high and the disc is hot. As the super-Eddington mass transfer continues, the system widens and the accretion disc becomes more extended, driving the tracks towards redder colors. In addition, self-irradiation is essentially suppressed. However, after the peak, the mass transfer rate starts to decrease, irradiation starts to contribute again and for systems with more massive donors the evolution towards the red slows down.

In order to model the multiwavelength properties of ULXs we also included the contribution of saturated Comptonization from an inner spherical corona.

The data/model comparison proceeds through three sequential steps: comparison of the photometry with the evolutionary tracks on the CMD diagram, age selection, search for the best fit of the multiwavelength SED.

We applied our model to a number of ULXs with well studied optical counterparts: NGC 4559 X−7, NGC 5204 X−1, HolmbergII X−1 and NGC 5907 ULX−2.

- **NGC 4559 X−7**: The optical photometry of this source, together with the X-ray data, point to super-Eddington accretion onto massive BHs for this system. We found that the observed properties are reproduced by a system accreting above Eddington ($\dot{m} \sim 900 - 1000$) onto a BH of $\sim 55 M_{\odot}$ from a donor of $\sim 5.5 M_{\odot}$. The system consists of a standard disc emitting most of the optical luminosity, an optically thick and extended outflow which covers part of the standard disc and almost the entire inner advection dominated disc, and an optically thick cool corona, with electron temperature of $\sim 1.2$ keV, which dominates the hard X-ray emission. The orbital period is fairly large, $\sim 18$ d. In fact, when accretion occurs at super-critical rates, the orbital separation increases rapidly. The system produces very high bolometric luminosity $(3 - 4) \times 10^{40}$ erg s$^{-1}$, which is in agreement with the observed data. The results obtained with the MESA tracks are in agreement with those obtained with the Eggleton evolutionary tracks (see AZ). This source was studied previously by other authors, and our results are in agreement with their findings. PZ found that the optical counterpart of X−7 is reproduced by a massive BH which accretes from a donor of 30-50 $M_{\odot}$ during the H-shell burning phase. Stobbart et al. (2006) analyzed some XMM-Newton observations of this source (which they refer to as NGC4559 X−1) finding that its spectral shape is consistent with super-Eddington accretion onto BHs with masses up to 80 $M_{\odot}$. However, the estimated value of the BH mass inferred from our model is strongly dependent on the assumed distance of the source, which affects the optical luminosity of the system and hence the match with the evolutionary tracks on the CMD. The distance of NGC 4559 is quite uncertain and estimates vary in the range $6 - 15$ Mpc. For a distance lower than the one assumed here (10 Mpc), like the redshift-independent distance adopted by Clark et al. (2018) ($d = 7.14$ Mpc), lower mass BHs, down to 20 $M_{\odot}$, would be inferred. In a recent work, Pintore et al. (2021) suggest the possibility that the compact object in NGC 4559 X−7 is even lighter, with a mass in the range 1.4 - 4 $M_{\odot}$ (a light BH or a NS). A dedicated investigation of this scenario is outside the goals of this paper and we plan to do it in the future.

- **NGC 5204 X−1**: The result obtained from the $\chi^2$ fit of the SED at the time of intersection on the CMD suggests accretion at marginally super-critical rates from a donor with mass of $\sim 14 M_{\odot}$ onto a BH with mass of $\sim 40 M_{\odot}$. The system is 6.8 Myrs old and accretion is taking place while the donor, whose initial mass is $\sim 30 M_{\odot}$, is reaching the TAMS. However, the fit is not statistically acceptable and the bolometric luminosity is not well reproduced. The reason for which the fit is not satisfactory is related to the fact that the hard X-ray spectrum is not well represented. The source is harder than what predicted by our model and seems to require an additional high-energy tail to fit the X-ray data or a different geometry for comptonizing material. The existence of such a tail was studied by other authors. Mukherjee et al. (2015) modelled it with an additional Comptonizing component on the basis of the spectral analysis of coordinated XMM and NuSTAR observations of NGC 5204 X−1. A high energy excess with respect to a model with two thermal components has been found also by Walton et al. (2018), and was modelled with a cut-off power law component, produced by a possible accretion column, should the compact object being a NS.

- **HolmbergII X−1**: The modelling of this source shows that this system is accreting at marginally super-Eddington rates. The BH may have a mass of about 55 $M_{\odot}$ while the donor star has $\sim 11 M_{\odot}$. The best fit of the SED returns a corona temperature $\sim 1$ keV. Kajava et al. (2012) studied the evolution of the spectral curvature of HolmbergII finding that the
In the X-ray spectral fitting package XSPEC the accretion disk with advection (diskpbb$^4$ with $p \approx 0.5$ in XSPEC) fits the data better than the standard accretion disc (diskbb$^5$). Moreover, adding a Comptonizing component reproduces the spectrum well if a low electron temperature is considered ($kT_e \approx 1.2$ keV). Their findings are in agreement with the results obtained with our model.

- NGC 5907 ULX-2: The observed multiwavelength SED is better reproduced with a system composed of a donor star with mass of about 4.5 $M_\odot$ which is accreting at super-Eddington rates onto a BH of about 36.5 $M_\odot$ according to the value suggested by Pintore et al. (2018) (where they adopted the model in A2 to infer a BH mass of 30 $M_\odot$). The system initially consisted of a 15 $M_\odot$ donor and a 30 $M_\odot$ BH. The accretion phase takes place while the donor is ascending along the Giant Branch. The binary has an orbital period of $\approx 24$ d, therefore the disc is very extended. As reported by Pintore et al. (2018) the color and luminosity of the optical counterpart are consistent with those of an O-B type star. From our modelling, it is clear that the contribution of the accretion disc to the optical emission is dominant. Therefore the overall scenario can be misinterpreted if optical emission is ascribed only to the donor star. The outer standard disc contributes substantially to the optical flux mimicking the emission of a massive donor.

In summary, we found that two out of four ULXs are well represented by systems with BH mass in the range between 35–40 $M_\odot$, while for the other two the best-fit solution points to more massive BHs, $\approx 55M_\odot$. Therefore, although the present sample of ULXs is very small and not representative of the whole population, the observational emission properties, together with binary evolution and age estimates, seem to suggest the existence of massive BHs in some sources. We finally explored the possibility to extend our model to the challenging case of PULXs. We could steadily evolve only systems with a maximum donor mass of 5 $M_\odot$, whose optical emission results to be too faint to be detected with HST at the observed distances of ULXs. This result is consistent with the non-detection of the counterpart of the Pulsar ULX NGC 5907 ULX-1 (Sutton et al. 2013a). We note that two PULXs have a detected optical counterpart: NGC 7933 P13 and NGC 1313 X-2 (Grisé et al. 2008; Motch et al. 2014; Sathyaprakash et al. 2019). The first one is accreting from a massive donor (18-23 $M_\odot$) (Israel et al. 2017b) and has been proved to be an eccentric binary system (Israel et al. 2017b; Hu et al. 2017). The optical counterpart of NGC 1313 X-2 is very luminous ($M_{V,B} < -4.5$) and cannot be reproduced with our evolutionary tracks for PULXs. Moreover, population studies reveal that its host environment is a young O-B association, aged $\approx 20$ Myr, pointing to a young massive star for the donor. If compared with our model of accreting BHs, the optical counterpart of X-2 would be represented by a 25 $M_\odot$ BH which accretes at marginally super-Eddington rates from a 12 $M_\odot$ donor. The apparent degeneracy intrinsic to this result is broken by the value of the orbital period (see also AZ), which would be too long to be consistent with the range of periods proposed by Sathyaprakash et al. (2019).

Related to this, we emphasize the importance of a multiwavelength and multi-disciplinary approach to unveil the nature of the binary systems that power ULXs. This would help to discern the nature of the accretor whereas the possibility to detect coherent pulsation is halted by the poor quality of the data and/or the geometry of the system with respect to the observer or by the fact that pulsed emission is in fact not present. Despite the difficulties encountered by us and several authors in modelling accreting binaries with massive donors and a pulsars, these two sources show that accretion from a massive donor onto a neutron star is feasible. Possible scenarios could be different from that proposed in this work. Quast et al. (2019) shows that nuclear timescale mass transfer is feasible for neutron star accretors with a different prescription for hydrogen and helium content of the donor star. El Mellah et al. (2019) invokes accretion driven by Wind Roche lobe overflow. Another possibility is accretion under the hypothesis of eccentric orbits. All these scenarios need to be investigated in detail in the future in a framework similar to the one proposed here to assess the formation routes of NS-massive donors systems.

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DATA AVAILABILITY

All of the data underlying this article are already publicly available from ESA’s XMM-Newton Science Archive (https://www.cosmos.esa.int/web/xmm-newton/xsa) and NASA’s HEASARC archive (https://heasarc.gsfc.nasa.gov/).

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APPENDIX A: $Z = 0.2 Z_\odot$, $BH = 20 M_\odot$

Effects of metallicity on the binary evolution of systems that undergo case A mass transfer. We show the representative case of accretion onto a BH of 20 $M_\odot$ for donors with solar and sub-solar ($Z = 0.2 Z_\odot$) metallicity. Metallicity does not induce important changes on the evolution of donors for case A mass transfer. Fig. A shows the evolution of the mass transfer rate for systems with donor with 8, 10, 20, 25 $M_\odot$ and 30 $M_\odot$. The mass transfer rate evolves similarly in the
two cases, with a slight delay in time and shortening in the duration of the main accretion episode.

APPENDIX B: EVOLUTIONARY TRACKS FOR A GIVEN BH MASS

Systems accreting onto a 10 \(M_\odot\) BH

The evolutionary tracks on the CMD for systems accreting onto a 10 \(M_\odot\) BH are shown in the upper left panel of Figs. 5 and 6. We notice first that the track of the 20 \(M_\odot\) donor does not appear in the CMD, while that of a 15 \(M_\odot\) donor is only marginally represented. During the first contact episode during MS, these systems accrete at very high super-Eddington rates (see the upper left panel of Fig. 1) so that the outflow engulfs the binary and we cannot follow their evolution with our model. We are left with the systems accreting from less massive donors: from 5 to 12 \(M_\odot\). When the donors are on the MS, the tracks are blue \((B-V \approx -0.3 : 0.0)\) and not very luminous \((M_V \approx -2 : -3.5)\). The 5 \(M_\odot\) donor represents an exception (see below): during Main Sequence it becomes redder \((B-V\) increases up to 0.5\) and its luminosity progressively decreases \((M_V \approx -1 : -2.3)\). When the donors evolve off the MS and the mass transfer becomes super-Eddington, colors are initially blue and then they become redder. The magnitudes are brighter than in MS, in the range \(M_V = -3.8 : -5.2\).

As mentioned above, the 5 \(M_\odot\) donor behaves in a different way. First, the radius of the disc at the TAMS is larger than that of the other systems. Moreover, the mass transfer rate is considerably sub-Eddington. These two facts imply that the accretion disc is relatively cold. Also the donor star, which at TAMS is a low mass star (see Fig. 3), is relatively weak and cold. Therefore, the \(V\) magnitude of the system is weak and colors are red \((B-V \sim 0.5)\). Given the low star and disc temperatures, the system with a 5 \(M_\odot\) donor is more luminous in the I band than in the V band, as it can be seen comparing Fig. 5 with Fig. 6.

Systems accreting onto a 20 \(M_\odot\) BH

Let now consider the CMDs for systems accreting onto a 20 \(M_\odot\) BH (upper right panel of Figs. 5 and 6). At variance with the previous case, the tracks belonging to all the donor stars appear in the diagram. In fact, the lower value of the mass ratios (Fig. 3) allows for a less eruptive initial mass transfer phase. We could evolve steadily the 15 \(M_\odot\) donor. The track of a 20 \(M_\odot\) donor is stopped only at the final stages of the giant branch. More massive donors (25 and 30 \(M_\odot\)) are evolved for a short time and then their evolution is stopped because the outflow engulfs the binary. The evolution of the optical properties of these systems are
similar to those described above for a 10 $M_\odot$ BH. The only difference is that V-I colors are redder than the those of systems with a 10 $M_\odot$ BH, because the discs are more extended. The evolution of the 5 $M_\odot$ donor during MS is different, because the system is accreting sub-Eddington (as for the 10 $M_\odot$ BH).

For the more massive donors ($M > 10 M_\odot$), the accretion in the post MS phases is characterized by blue colors and bright $M_V$ magnitude ($B - V \sim -0.23 : 0.0$, $M_V \sim -5.0 : -6.3$). For lower mass donors ($M \leq 10 M_\odot$), systems are comparatively redder and fainter ($B - V \sim 0 : 0.6$, $V - I \sim -0.2 : 0.8$, $M_V \sim -4.0 : -5.3$, $M_I \sim -4.5 : -6.1$).

**Systems accreting onto a 30 $M_\odot$ BH**

For a 30 $M_\odot$ BH accretion is more stable from the beginning of the RLOF for donors up to 30 $M_\odot$ (middle left panel of Fig. 1). For a given mass the binary separation is larger. This prevents the outflow from engulfing the binary during MS. All the systems with donor mass $M_d \leq 25 M_\odot$ can be evolved with our model, while the system with donor mass $M_d = 30 M_\odot$ is stopped at the middle of the giant phase. For donors less massive than 20 $M_\odot$ during MS, the flux emitted by the disc overcomes that emitted by the star in the V band increases significantly. Magnitude and colors, during MS are in the range: $B - V \sim -0.3 : -0.1$, $V - I \sim -0.45 : 0.5$, $M_V = -2.5 : -6.3$, $M_I \sim -2.3 : -6.1$, while during the post-MS phases are in the range: $B - V \sim -0.25 : -0.1$, $V - I \sim -0.4 : 0.1$, $M_V = -6.0 : -8.2$, $M_I \sim -6.1 : -7.9$.

**APPENDIX C: FLUX RATIOS**

In this Appendix we show the ratios between the flux emitted by the disc and that emitted by the star in the V band. These figures help to understand the evolutionary tracks on the CMD described in Sec. 2.2.

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Systems accreting onto a 100 $M_\odot$ BH

Finally, we describe the evolution of systems accreting onto a 100 $M_\odot$ BH, which is the maximum BH mass considered in this work (lower right panels in Figs. 5 and 6). Even for the high mass transfer rate which characterizes the initial evolution of a 30 $M_\odot$ donor, see Fig. 1, the outflow does not engulf the system. We can evolve it up to the moment in which the donor starts He-burning in the nucleus, which is the endpoint of the evolutionary tracks we evolved with MESA. The behaviour is similar to that of the systems with a 50 or 70 $M_\odot$ BH. The systems become very red and the luminosity in the V band increases significantly. Magnitude and colors, during MS are in the range: $B - V \sim -0.3 : -0.1$, $V - I \sim -0.45 : 0.5$, $M_V = -2.5 : -6.3$, $M_I \sim -2.3 : -6.1$, while during the post-MS phases are in the range: $B - V \sim -0.25 : -0.1$, $V - I \sim -0.4 : 0.1$, $M_V = -6.0 : -8.2$, $M_I \sim -6.1 : -7.9$.
Figure C1. Evolution of the ratio between the flux emitted by the disc and that emitted by the donor star in the Johnson V filter. The trend of the tracks while the donor is on the Main Sequence is considerably influenced by the flux ratio.