The black hole in NGC 1313 X-2: constraints on the mass from optical observations

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ABSTRACT

We present a theoretical study on the nature of the ultraluminous X-ray source NGC 1313 X-2. We evolved a set of binaries with high-mass donor stars orbiting a 20 M⊙ or a 50–100 M⊙ black hole (BH). Using constraints from optical observations, we restricted the candidate binary system for NGC 1313 X-2 to be either a 50–100 M⊙ BH accreting from a 12–15 M⊙ main-sequence star or a ∼20 M⊙ BH with a 12–15 M⊙ giant donor. If the modulation of 6.12 ± 0.16 d recently identified as the orbital period of the system is confirmed, a ∼20 M⊙ BH model becomes unlikely and we are left with the only possibility that the compact accretor in NGC 1313 X-2 is a massive BH of ∼50–100 M⊙.

Key words: galaxies: X-rays: binaries – X-rays: galaxies.

1 INTRODUCTION

Ultraluminous X-ray sources (ULXs) are off-nuclear extragalactic X-ray sources with isotropic bolometric luminosities in excess of the Eddington limit for a stellar mass black hole (BH). An empirical approach defines ULXs as sources with X-ray luminosities in the range $L_X \sim 10^{39}$–$10^{41}$ erg s$^{-1}$. These sources are quite common in starburst and late-type galaxies and are thought to be mostly binaries with a donor star transferring matter on to a BH. There is not yet a general consensus on the mechanism that drives such large luminosities (see e.g. Zampieri & Roberts 2009, and references therein). Some proposed explanations involve $\lesssim 20$ M⊙ BHs with thick discs producing beamed emission, slim discs with photon bubble trapping and super-Eddington emission (see e.g. Poutanen et al. 2007, and references therein), or two-phase super-Eddington radiatively efficient discs (Socrates & Davis 2006). The most intriguing possibility would be the presence of the so-called intermediate mass black holes (IMBHs): even if ULXs are genuine isotropic emitters, the Eddington limit would not be violated if the accretor has a mass of $\sim 10^2$–$10^3$ M⊙. An alternative formation scenario has been proposed and recently explored in detail in which a portion of ULXs contains $\sim 30$–$90$ M⊙ BHs formed in a low metallicity environment and accreting in a slightly critical regime (Mapelli, Colpi & Zampieri 2009; Zampieri & Roberts 2009). The binary nature of ULXs was supported by the possible orbital periodicity at 62 d detected by Kaaret et al. (2006a), Kaaret, Simet & Lang (2006b) and Kaaret & Feng (2007) for the ULX M82 X-1. Constraints from the orbital period, X-ray luminosity and optical photometry suggested that the most likely explanation for the compact accretor in this ULX is an IMBH of mass larger than 200 M⊙ (Patruno et al. 2006; see however Begelman, King & Pringle 2006 for an alternative interpretation without an IMBH). Patruno & Zampieri (2008) and Madhusudhan et al. (2008) demonstrated how several further constraints can be put on the nature of ULXs from the identification of optical counterparts. In the majority of cases, optical identifications indicate the existence of high mass donor stars ($M \gtrsim 8$ M⊙ ). The optical emission coming from the donor is expected to be strongly contaminated by the contribution of the external regions of the accretion disc, and by reprocessing of the X-ray radiation generated in the innermost portion of the disc. Contribution from the X-ray irradiation of the donor star surface also plays a role (Copperwheat et al. 2005; Patruno & Zampieri 2008).

The identification of a unique optical counterpart however is not an easy task, as ULXs are often observed in crowded regions of star formation. The ULX NGC1313 X-2 (henceforth referred to as X-2) is one of the most promising sources in this respect. Zampieri et al. (2004) and Mucciarelli et al. (2005) first identified two candidate counterparts for this source (C1 and C2). Mucciarelli et al. (2007) and Liu et al. (2007) pinpointed C1 as the most likely counterpart by means of a model of the optical emission and a refined analysis of the HST and Chandra astrometry. Through an independent theoretical investigation, we showed that the object C1 is the only one consistent with the properties predicted by a binary evolution model (Patruno & Zampieri 2008). Mucciarelli et al. (2005) estimated a mass of $\sim 20$ M⊙ for C1, later refined to be in the interval 10–18 M⊙ by Mucciarelli et al. (2007). Grisi et al. (2008) identified the donor as a star of $8$–$16$ M⊙ whereas Liu et al. (2007) proposed a somewhat smaller mass ($\sim 8$ M⊙). Grisi et al. (2008) derived an age of $20 \pm 5$ Myr for the star cluster where X-2 resides and hence an upper limit for the donor mass of $\sim 12$ M⊙. However, all these observational studies did not consider...
the effects of binary evolution on the donor star colours and age. Taking into account the effects of binary evolution and irradiation, we estimated the mass of C1 to be \(<15\,M_\odot\) (Patruno & Zampieri 2008). Finally, from an estimate of the amount of energy injected in the bubble nebula surrounding this ULX, Pakull, Grisé & Motch (2006) derived a time-scale for the active phase of X-2 of the order of \(<10^8\) yr. Pakull et al. (2006) further confirmed C1 as the likely counterpart reporting evidence of a broad 4686 He\(\alpha\) line in the optical spectrum of X-2.

Recently, Liu, Bregman & McClintock (2009) tentatively identified a modulation in the \(B\) band light curve of X-2 with a period of 6.12 \pm 0.16 d. If this is confirmed, X-2 will be the most constrained ULX known to date. In this Letter, we will use all the available data of X-2 coming from optical observations (including the \(<6\) d orbital period) and compare them with the evolution of an ensemble of irradiated X-ray binary models in order to constrain the nature of the compact accretor.

2 BINARY EVOLUTION AND X-RAY REPROCESSING

The binary evolution model adopted here is the same as outlined in Patruno & Zampieri (2008) (to which we refer for details; see also Podsiadlowski, Rappaport & Han 2003; Patruno et al. 2005; Rappaport, Podsiadlowski & Pfahl 2005; Madhusudhan et al. 2006; Patruno et al. 2006; Madhusudhan et al. 2008, for a discussion on BH binary evolution models). We consider two ensembles of binaries: the first with BHs of 20\(\,M_\odot\) and the second with BHs of 100\(\,M_\odot\). The donor stars have initial masses between 8 and 25\(\,M_\odot\). Two different values of the (zero age) metallicity, both subsolar, are considered: \(Z = 0.004\) (Ryder 1993) and \(Z = 0.01\) (close to the value \(Z = 0.008\) estimated by Hadfield & Crowther 2007; Walsh & Roy 1997). If the donor starts a contact phase via Roche-lobe overflow (RLOF), we assume that a geometrically thin optically thick accretion disc forms around the BH. The efficiency for the conversion of rest mass into radiation is fixed at 10 per cent. The accretion rate is instantaneously taken to be equal to the mass-transfer rate from the companion. When the accretion rate \(\dot{M}\) exceeds the Eddington rate \(\dot{M}_{\text{Edd}}\), we impose \(\dot{M} = \dot{M}_{\text{Edd}}\) and assume that the excess mass is expelled from the system. In our simulations, all the binaries that start RLOF on the main sequence (MS) have also a second episode of mass transfer after the terminal age main sequence (TAMS). Therefore, we term such binary models as Case AB while those starting the first contact phase after the TAMS are termed Case B.

The UV/optical luminosity is computed summing to the donor emission the contribution of the accretion disc, and including the effects of the reprocessed X-ray radiation (see Patruno & Zampieri 2008 for details). In the present version of the code, we improved the accuracy in the calculations of the optical colours of the irradiated accretion disc, which are now \(<0.1\) mag redder than those previously reported. None of the results and conclusions published in Patruno & Zampieri (2008) are significantly affected by this revision.

For all the donors considered here, the disc contribution to the UV/optical emission can be dominant for BHs of \(<20\,M_\odot\), whereas it is less important but still significant for 20\(\,M_\odot\) BHs (Patruno & Zampieri 2008). The albedo of the irradiated layers is fixed at \(f_a = 0.9\). To investigate the effects of a different albedo, we evolved some binaries with \(f_a = 0.7\) and 0.95. As reference, we chose five values for the inclination angle of the binary, \(i = 0^\circ, 30^\circ, 45^\circ, 60^\circ, 80^\circ\). For each angle, we computed the optical emission summing the average luminosity of the irradiated and non-irradiated surfaces of the donor to the flux emitted from the visible part of the accretion disc.

3 OBSERVATIONAL CONSTRAINTS

X-2 is located in the barred spiral galaxy NGC 1313 at a distance of 3.7–4.27 Mpc (Tully 1988; Méndez et al. 2002; Rizzi et al. 2007). Its observed X-ray luminosity varies between a few \(10^{39}\) erg s\(^{-1}\) and \(3 \times 10^{40}\) in the 0.3–10 keV band (Feng & Kaaret 2006; Mucciarelli et al. 2007). Recently, Liu et al. (2009) found a possible periodicity of 6.12 \pm 0.16 d in the \(B\)-band light curve of C1 that was interpreted as the orbital period of the binary. Three cycles were detected in the \(B\) band, while no modulation was found in \(V\). According to Liu et al. (2009), the period is 12.24 \pm 0.16 d if the X-ray irradiation of the donor is unimportant, while it is 6.12 \pm 0.16 d in case of significant irradiation. Previous studies carried out on the available HST and Very Large Telescope (VLT) observations led to negative results (Grisé et al. 2008). More recently, lack of significant photometric variability on a new sequence of VLT observations has been reported by Grisé et al. (2009). Therefore, we consider the detection of Liu et al. (2009) with caution and are aware that it will need to be confirmed before any definite conclusion can be drawn.

In the following, we will use the \(V\)- and \(B\)-band photometry of C1 as determined by Mucciarelli et al. (2007). As the source is variable, we have further corrected the magnitudes and colours by using the average value of \(V\) and by propagating the errors on \(V\) and \(B\). The error in the absolute magnitudes is taken to be equal to the maximum uncertainty in the different distance determinations of NGC 1313 (Tully 1988; Méndez et al. 2002; Rizzi et al. 2007). Concerning the reddening, two different estimates of the colour excess were derived in the literature: \(E(B-V) = 0.1\) (Mucciarelli et al. 2007; Grisé et al. 2008) and \(E(B-V) = 0.3\) (Liu et al. 2007). As the analyses of Mucciarelli et al. (2007) and Grisé et al. (2008), based in part on independent methods converge towards the same value, in the following we chose \(E(B-V) = 0.1\).

1 The adopted \(M_V\) magnitude is therefore in the range of \(-4.38\) to \(-4.79\) and the \(B - V\) colour is \(-0.13 \pm 0.06\).

4 RESULTS

4.1 Case AB mass transfer

In Fig. 1, we show the results of the binary evolution calculations (including the effects of irradiation) for \(Z = 0.01\) and Case AB mass transfer, and for an inclination \(i = 0^\circ\). The track for a 15\(\,M_\odot\) donor with a 100\(\,M_\odot\) BH passes through the C1 errorbox during the MS, whereas the 20\(\,M_\odot\) BH matches the observations during the giant phase. When this happens, the orbital period for the 15\(\,M_\odot\) donor and 100\(\,M_\odot\) BH model is \(<5.9\) d, very close to the determination of Liu et al. (2009). The donor age is \(<16\) Myr, which is consistent with the estimate of Grisé et al. (2008) for the host OB association.

\[1\] If we consider \(E(B-V) = 0.3\), all the models with a 20\(\,M_\odot\) BH become incompatible with the position of C1, and the minimum donor mass required to match the observations for a 100\(\,M_\odot\) BH becomes \(M > 25\,M_\odot\) with characteristic age \(t < 10\) Myr (H-shell burning phase), in strong disagreement with the observed cluster age of 20 \pm 5 Myr, reported by Grisé et al. (2009).
We decreased the BH mass to 50–70 M☉, keeping the donor mass at 15 M☉, to verify if a slightly lighter BH would produce a significantly different result. In all cases, the donor colours, age and orbital period match the observations when the star is close to the TAMS, with values similar to those of the 100 M☉ BH case. The mass transfer of the 15 M☉ donor at the position of C1 is typically between $M \sim 2 \times 10^{-7}$ and $\sim 2 \times 10^{-8}$ M☉ yr$^{-1}$. This is consistent with the measured average luminosity of X-2, $\sim 4 \times 10^{39}$ erg s$^{-1}$ (Mucciarelli et al. 2007), which requires $M \sim 10^{-6}$ M☉ yr$^{-1}$. When considering the tracks with a smaller metallicity ($Z = 0.004$), the situation is similar and the effect on the stellar colours is minimal. Therefore, we will consider for reference only tracks calculated for $Z = 0.01$.

The $M_V$-band magnitude of ULXs is lower (i.e. the luminosity larger) for 50–100 M☉ BHs than for 20 M☉ BHs (see Fig. 1 and Patruno & Zampieri 2008). This is mainly due to the larger optical contamination of the irradiated disc and for an intrinsic binary evolution effect that makes a companion star around a 50–100 M☉ BH brighter than that around a 20 M☉ BH when RLOF starts at a fixed donor age. For a 50–100 M☉ BH, the (irradiated) disc flux exceeds the (irradiated) donor flux up to 100–300 per cent, depending on the photometric band and the mass ratio considered, while for a 20 M☉ BH it is between 20 and 130 per cent of the donor flux at maximum accretion rate. A small increase of the order of $\sim 0.1$ mag in $B - V$ occurs when increasing the BH mass.

All the results remain essentially unchanged if we increase the inclination angle up to 80°. Only for $i \gtrsim 80°$, there is a significant decrease of the accretion disc contribution and hence of the luminosity ($\propto \cos i$), which is particularly significant for binaries around a 50–100 M☉ BH. A light curve folded over the orbital period was simulated calculating the area of the irradiated non-irradiated surface seen by a distant observer as a function of orbital phase and inclination, integrating the specific intensity separately over the two surfaces and summing up the resulting fluxes. At large inclination angles ($i \gtrsim 60°$), the light curve is approximately sinusoidal and the maximum amplitude of the orbital modulation in the $B$ band is $\sim 0.04$ mag (including disc emission), about a factor of 2 smaller than the amplitude of the observed modulation (Liu et al. 2009). For a 20 M☉ BH, the contribution from the disc is less important and the amplitude of the modulation is close to the observed value ($\sim 0.1$ mag). However, if moderate beaming is assumed, the X-ray radiation is no longer able to hit the donor surface and the orbital modulation caused by X-ray heating is expected to be largely suppressed. To verify this scenario, we evolved a set of tracks with a 20 M☉ BH and no effect of irradiation for Case AB. The tracks of a 15 M☉ donor are compatible with C1 when the star is on the giant branch with an age of $\sim 19$ Myr, although the period of the binary is $\sim 15–23$ d.

When considering binaries with irradiation, the evolutionary tracks do not show dramatic changes in position and shape on the colour–magnitude diagram (CMD) when varying the albedo $f_a$. The main effect is an increase (up to a factor of 2 for $f_a = 0.7$) of the amplitude of the orbital modulation caused by X-ray irradiation. The difference in the $B - V$ colour is $\sim 0.1$ mag or less, while the change in the $M_V$ magnitude is smaller than 1 mag. When comparing the tracks with the position of C1 on the CMD, this translates into an uncertainty of only a few solar masses in the determination of the donor mass. This is true also for the Case B discussed below. Both 20 M☉ and 50–100 M☉ BH models are still crossing C1 when the donor is on the giant branch and on the MS, respectively.

By considering all these small sources of uncertainties for the stellar tracks, we can consider the position of C1 also consistent with donors on the MS with masses of 12–20 M☉ and a 50–100 M☉ BH. However, when the track of the 20 M☉ donor crosses C1, the donor age is 4–11 Myr with a period 1.5–5.9 d. The donor is therefore too young to be compatible with the stellar cluster age (15–25 Myr). For the 12 M☉ donor, the age is 20–22 Myr and the orbital period is 3.1–5.5 d.

As mentioned above, the photometry of C1 is not consistent with the tracks relative to a 20 M☉ BH for donors on the MS. For these models, the mass transfer rate never exceeds the Eddington limit by more than a factor of 2 during the MS for donor masses $M \lesssim 15$ M☉. This means that even in case of genuinely super-Eddington accretion, the amount of X-ray irradiation would never greatly exceed the value used in our calculations.

The same is true for the orbital period. At the TAMS, it increases with the BH mass, and it is around 4.5–5 d for a BH of 20 M☉ and 5–6 d for a 100 M☉ BH. Therefore, all the 20 M☉ BH binaries need to be in the H-shell burning phase to be consistent with the observations. The donors compatible with the position of C1 have ages in the range of 12–36 Myr and orbital periods of 5–20 d, with a mass transfer rate always above the Eddington limit. Donors of 10 and 20 M☉ can immediately be excluded since they are too old ($\gtrsim 12$ Myr) or too young ($\lesssim 12$ Myr) to be compatible with the star cluster age (15–25 Myr).

Figure 1. Colour–magnitude diagram (CMD) for binaries with a 100 M☉ (left-hand panel) and a 20 M☉ BH (right-hand panel), undergoing Case AB mass transfer. The black triangle corresponds to the optical counterpart C1 with its 1σ errorbar. The assumed distance for X-2 is 3.7 Mpc and the errorbar in $M_V$ reflects the maximum uncertainty in the distance determination of NGC 1313 (see text). All the tracks are plotted only during the contact phases. The effects of irradiation and the optical contamination of the accretion disc are included. The donors are: 25 M☉ (yellow), 20 M☉ (cyan), 15 M☉ (pink), 12 M☉ (blue), 10 M☉ (green) and 8 M☉ (red).
4.2 Case B mass transfer

In Fig. 2, we show the results of the binary evolution calculations for Case B mass transfer. We assume again \( Z = 0.01 \) and an inclination \( i = 0^\circ \). The RLOF starts when the donor leaves the MS and its envelope expands crossing the Hertzsprung-Gap. The figure shows that 50–100 \( M_\odot \) BH binaries are too bright (\( \sim 1 \) mag) to account for the position of C1 on the CMD. The disc flux may exceed the donor flux up to a factor of 10. These models can therefore be excluded as possible candidates for X-2. The tracks of 20 \( M_\odot \) BH binaries with donors of \( 8 M_\odot \leq M \leq 12 M_\odot \) are compatible with the position of C1 (with a relative flux contribution from the disc reaching \( \sim 180 \) per cent at maximum accretion rate). As for Case AB mass transfer, consistency with the photometry of C1, the observed value of the orbital period and the age of field stars are never achieved for donors of 8, 15, 20 and 25 \( M_\odot \). For the 10 and 12 \( M_\odot \) model, the donor age is \( \sim 25 \) and 18 Myr, respectively, when the orbital period is \( P_{\text{orb}} \sim 6.1 \) d and the magnitude and colours are compatible with C1. However, the binaries have spent only a tiny amount of time (\( \sim 3000 \) yr for the 10 and 12 \( M_\odot \) donors) in RLOF contact when all the parameters are within the observed range.

5 DISCUSSION

We demonstrated that, when using the CMD and the constraints from the characteristic ages of the parent stellar cluster and the bubble nebula, the binary evolution of X-2 in NGC 1313 is described in terms of two possibilities for a Case AB scenario:

(i) mass transfer of a MS donor of \( \sim 12–15 M_\odot \) on to a \( \sim 50–100 M_\odot \) BH,

(ii) mass transfer of a H-shell burning donor of \( \sim 12–15 M_\odot \) on to a \( \sim 20 M_\odot \) BH.

Case B mass transfer for a 50–100 \( M_\odot \) BH is finally ruled out as the shift between the CMD tracks and the position of the optical counterpart is too large. This result relies solely on the position of the counterpart C1 on the CMD and assumes that all the binaries are X-ray irradiated and that their emission is contaminated by the accretion disc. Also Case B mass transfer for a 20 \( M_\odot \) BH can be ruled out considering the too short-lived RLOF phase which appears in contradiction with the \( \sim 10^6 \) yr age of the bubble nebula surrounding X-2 (Pakull et al. 2006). For Case AB mass transfer, the first contact phase during the MS is sufficiently long to inject the required energy in the bubble nebula and therefore makes the 20 \( M_\odot \) BH on to a \( 12–15 M_\odot \) H-shell donor a possible candidate for X-2. However, a strongly beamed system would not be consistent with the observations if the contribution to the nebular emission from the photo-ionization by the ULX is important, as the nebula is essentially isotropically illuminated (Pakull et al. 2006).

Note that Cases B and AB binary colours tend to become redder as the evolution proceeds, as a consequence of surplus mass ejection. This is in contrast to what was reported by Madhusudhan et al. (2008) who assumed that all the matter leaving the donor is retained by the BH and contributes to the optical contamination. When the donor leaves the MS, the mass transfer rate increases by up to one to two orders of magnitude. This means that in our model there is a substantial mass loss from the binary that does not contribute to the X-ray luminosity and to the reprocessing. This leads to redder colours for the binary and to a stable mass transfer with a lack of a common envelope phase (see van der Sluys, Verbunt & Pols 2005; Lommen et al. 2005 for a discussion).

If we use the tentative identification of the orbital period of Liu et al. (2009) as further constraint, binaries with a massive 50–100 \( M_\odot \) BH and a \( \sim 12–15 M_\odot \) donor close to the TAMS are compatible with the observations (\( \sim 6 \) d), while all the Case AB binaries with a 20 \( M_\odot \) BH are excluded (\( \sim 8 \) d).

In general, the orbital modulation in the optical light curve is caused by X-ray irradiation and ellipsoidal variations. Simulating a complete light curve is beyond the purpose of the present investigation. As discussed in Section 4.1, we computed the amplitude of the modulation induced by X-ray irradiation alone (\( \sim 0.05–0.15 \) mag for \( i \gtrsim 45^\circ \)). Ellipsoidal variations can be estimated from Bochkarev, Karitskaia & Shakura (1979) and, for the typical mass ratios considered here, have amplitudes \( \sim 0.1–0.2 \) mag (\( i \gtrsim 45^\circ \)). So, the two effects are comparable. In both cases, the reported values refer to the amplitude of the modulation without considering the accretion disc contribution. If the latter is included, the amplitude is reduced by a factor of \( \sim 2 \). Ellipsoidal variations induce two maxima and two minima per orbital cycle and therefore the observed modulation of \( \sim 6 \) d would correspond to an orbital period of 12 d. However, depending on the parameters, the secondary minimum may be largely suppressed and hence, within the photometric errors, the observed modulation would correspond to the \( \sim 6 \) d orbital period adopted by Liu et al. (2009). Clearly, more measurements are needed in order to reach a definitive conclusion. If the orbital period were \( \sim 12 \) d, it would be compatible with a Case AB binary with a 20 \( M_\odot \) (or slightly larger) BH and isotropic irradiation (\( \sim 8–20 \) d), while it would remain too small to be consistent with a \( \sim 10–12 M_\odot \) BH.
similar system in case beaming of the X-ray flux prevents irradiation (15–23 d).

For 50–100 M\(_{\odot}\) BHs, the expected amplitude of the orbital modulation is larger in the \(B\) band than in the \(V\) or \(R\) bands because, at longer wavelengths, where the donor spectrum decays more rapidly than the irradiated disc spectrum, the contamination from the disc is comparatively stronger. However, the difference in the amplitude between the \(B\) and \(V\) band may not be sufficient to explain a detection in the \(B\) band and a simultaneous non-detection in the \(V\) band. Further investigation is needed to assess this point. In the present assumptions, the most favourable optical band where to search for the orbital modulation appears to be the \(U\) and \(B\) bands, where the ratio between donor and disc emission is maximum. It is interesting to note also that, because of the disc contamination, the optical spectrum is characterized by a rather flat continuum with \(\propto \nu^{-1}\), clearly distinguishable from a Rayleigh–Jeans tail. All these predictions may be easily tested with further photometric and spectroscopic follow-ups of object C1. Finally, if spectroscopic data of the donor of NGC 1313 X-2 will support an identification of a MS star, the possibility that NGC 1313 X-2 hosts a 50–100 M\(_{\odot}\) BH is strongly favoured, independently of the period determination, whereas a giant donor will immediately rule out the possibility of a BH this massive. We note however that we did not perform a complete survey of the parameter space evolving Case AB systems with BH masses between 20 and 50 M\(_{\odot}\). In fact, depending on the actual value of the orbital period, for values of the BH in this mass range, there may also be agreement with observations. A systematic investigation of this type is postponed to when a more robust assessment of the orbital period will be available.

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