

Discovery of a 6.4 h black hole binary in NGC 4490

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ABSTRACT

We report on the discovery with *Chandra* of a strong modulation (~ 90 per cent pulsed fraction) at ~ 6.4 h from the source CXOU J123030.3+413853 in the star-forming, low-metallicity spiral galaxy NGC 4490, which is interacting with the irregular companion NGC 4485. This modulation, confirmed also by *XMM-Newton* observations, is interpreted as the orbital period of a binary system. The spectra from the *Chandra* and *XMM-Newton* observations can be described by a power-law model with photon index $\Gamma \sim 1.5$. During these observations, which span from 2000 November to 2008 May, the source showed a long-term luminosity variability by a factor of ~ 5 , between $\sim 2 \times 10^{38}$ and 1.1×10^{39} erg s⁻¹ (for a distance of 8 Mpc). The maximum X-ray luminosity, exceeding by far the Eddington limit of a neutron star, indicates that the accretor is a black hole. Given the high X-ray luminosity, the short orbital period and the morphology of the orbital light curve, we favour an interpretation of CXOU J123030.3+413853 as a rare high-mass X-ray binary system with a Wolf–Rayet star as a donor, similar to Cyg X–3. This would be the fourth system of this kind known in the local Universe. CXOU J123030.3+413853 can also be considered as a transitional object between high-mass X-ray binaries and ultraluminous X-ray sources (ULXs), the study of which may reveal how the properties of persistent black hole binaries evolve entering the ULX regime.

Key words: galaxies: individual: NGC 4490 – X-rays: binaries – X-rays: individual: CXOU J123030.3+413853.

1 INTRODUCTION

NGC 4490, at a distance of 7–10 Mpc,¹ is a spiral galaxy interacting with the irregular galaxy NGC 4485 (de Vaucouleurs, de Vaucouleurs & Corwin 1976; Tully & Fisher 1988; de Vaucouleurs et al. 1991). At 8 Mpc (the distance we assume throughout, following many previous studies), the angular separation between the pair (~ 3.6 arcmin) corresponds to a projected distance of ~ 8 kpc, while the sizes of NGC 4490 and NGC 4485 are ~ 15 and ~ 5.6 kpc, respectively (Clemens, Alexander & Green 1999). Radio and infrared observations indicate an enhanced star-forming activity (Viallefond, Allen & de Boer 1980; Duval 1981; Klein 1983; Thronson et al. 1989) at a rate of $\sim 5 M_{\odot} \text{ yr}^{-1}$ (Clemens & Alexander 2002).

The first X-ray observations of NGC 4485/4490 with good angular resolution were carried out with *ROSAT* and resulted in the detection of five compact X-ray sources (Read, Ponman & Strickland 1997; Roberts & Warwick 2000; Liu & Bregman

2005). Subsequent observations with *Chandra* increased the number of resolved sources to 38 (Roberts et al. 2002; Fridriksson et al. 2008; Richings et al. 2010). Among these sources, there is CXOU J123030.3+413853, which was discovered in NGC 4490 by Roberts et al. (2002) with the first *Chandra* observation, performed in 2000 November. The object is located at ~ 1.1 arcmin (~ 2.5 kpc) from the optical nucleus of NGC 4490. In a study of the variability of the X-ray sources of NGC 4490/4485, Fridriksson et al. (2008) observed both short- and long-term flux variability in CXOU J123030.3+413853 but, overall, since its discovery the source did not attract particular interest.

Here, we report on a comprehensive analysis of all the *Chandra* and *XMM-Newton* data of CXOU J123030.3+413853. We present evidence that its X-ray emission is modulated at a period of ~ 6.4 h (~ 23 ks) which can be interpreted as the orbital period of a binary system. We also found that in several observations CXOU J123030.3+413853 approached, and perhaps exceeded, an X-ray luminosity (L_X) of $\sim 10^{39}$ erg s⁻¹, which is the traditional threshold for ultraluminous X-ray sources (ULXs; see Feng & Soria 2011 for a recent review). These sources are matter of debate as they may harbour intermediate-mass ($\sim 10^2$ – $10^5 M_{\odot}$) black holes (BHs), bridging the gap between stellar-mass BHs and the

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¹Distances from the NASA/IPAC Extragalactic Database (NED), see <http://ned.ipac.caltech.edu/>.

supermassive BHs found in galactic nuclei (see e.g. Miller & Colbert 2004; van der Marel 2004). However, apart from a handful of extremely luminous ($L_X > 5 \times 10^{40} \text{ erg s}^{-1}$; Sutton et al. 2012) or hyperluminous ($L_X > 10^{41} \text{ erg s}^{-1}$; Farrell et al. 2009) objects, observationally BHs of several hundreds to thousands M_\odot are not required for the majority of ULXs (e.g. Fabbiano 2005), which remain consistent with alternative interpretations – either unusually massive stellar BHs ($\sim 20\text{--}100 M_\odot$) or a different accretion state (e.g. Zampieri & Roberts 2009; Feng & Soria 2011).

2 OBSERVATIONS

Chandra observed the galaxy pair NGC 4485/4490 with its Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) instrument three times (between 2000 and 2004), for a total exposure of approximately 100 ks (Roberts et al. 2002; Fridriksson et al. 2008; Gladstone & Roberts 2009; Richings et al. 2010; Yoshida et al. 2010). Details of the observations are summarized in Table 1. In all observations, the ACIS was operated in the standard timed exposure full-frame mode, with a CCD readout time of 3.24 s. In the first observation, the events were telemetered in ‘faint’ mode,

while the other two observations were performed with the ‘very faint’ telemetry format. Each time, CXOU J123030.3+413853 was positioned on the back-illuminated chip S3. The data were re-processed with the *Chandra* Interactive Analysis of Observations software package (CIAO, version 4.5). Fig. 1 shows the field of CXOU J123030.3+413853 in the 0.3–8 keV energy band. The source counts were selected in an ~ 2 arcsec radius region and the background in an annulus with inner (outer) radius of 5 (10) arcsec. The spectra, the ancillary response file and the spectral redistribution matrices were created using *SPEXTRACT*.

XMM-Newton observed NGC 4485/4490 two times: in 2002, for about 18 ks (Winter, Mushotzky & Reynolds 2006; Gladstone & Roberts 2009; Yoshida et al. 2010), and in 2008, for 37 ks (Table 1). For this work, we used only the data from the European Photon Imaging Camera, which consist of two MOS (Turner et al. 2001) and one pn (Strüder et al. 2001) CCD cameras. The front-illuminated MOS cameras were operated both times in full-frame mode (integration time: 2.6 s), while the back-illuminated pn was set in ‘extended’ full-frame mode in 2002 (integration time: 0.2 s) and in full frame in 2008 (integration time: 73 ms); the medium optical blocking filters were used for all observations. Both observations (but particularly the second) were affected by rather intense soft-proton flares. Since the removal of the intervals of flaring background significantly alters the light curves, we chose to clean the data for the spectral analysis (by applying intensity filters to the event lists) and to limit the timing analysis to the unfiltered MOS data, since the MOS cameras are less affected by proton flares. In order to reduce the contamination from the hot interstellar medium emission of NGC 4490 and from nearby sources (Fig. 1), the source photons were accumulated for each camera in small circular regions (10 arcsec radius, ~ 60 per cent of the enclosed energy fraction at 1.5 keV). The background counts were estimated from source-free composite regions in the same chip as the source. The data were processed using the *XMM-Newton* Science Analysis Software (SAS, version 12). The ancillary response files and the spectral

Table 1. Summary of the observations used in this work.

Mission / Obs. ID	Date	Exp. (ks)	Count rate ^a (count s ⁻¹)
<i>Chandra</i> 1579	2000 Nov 03	19.5	$(8.2 \pm 0.7) \times 10^{-3}$
<i>XMM</i> / 0112280201	2002 May 27	17.5	$(1.1 \pm 0.1) \times 10^{-2}$
<i>Chandra</i> 4725	2004 Jul 29–30	38.5	$(9.4 \pm 0.5) \times 10^{-3}$
<i>Chandra</i> 4726	2004 Nov 20	39.6	$(1.6 \pm 0.2) \times 10^{-3}$
<i>XMM</i> / 0556300101	2008 May 19	37.4	$(1.1 \pm 0.1) \times 10^{-2}$

^aNet source count rate in the 0.3–8 keV energy band using the extraction regions described in the text; for the *XMM-Newton* observations we give the pn rate. The values are not corrected for point spread function and vignetting effects.

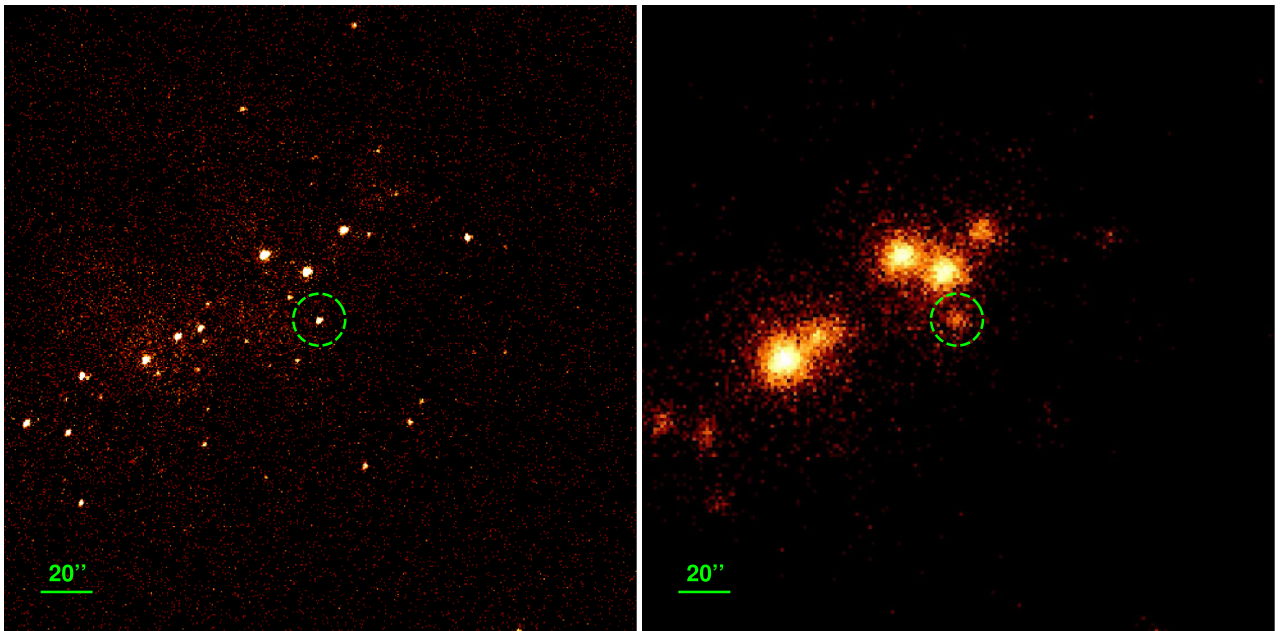


Figure 1. Field of CXOU J123030.3+413853, marked by the circle (20 arcsec diameter) as imaged by *Chandra* (left) and *XMM-Newton* (right) in the 0.3–8 keV energy band (all observations were combined). Each image side is 4 arcmin wide. X-ray emission from the hot interstellar medium of NGC 4485/4490 is apparent in both images.

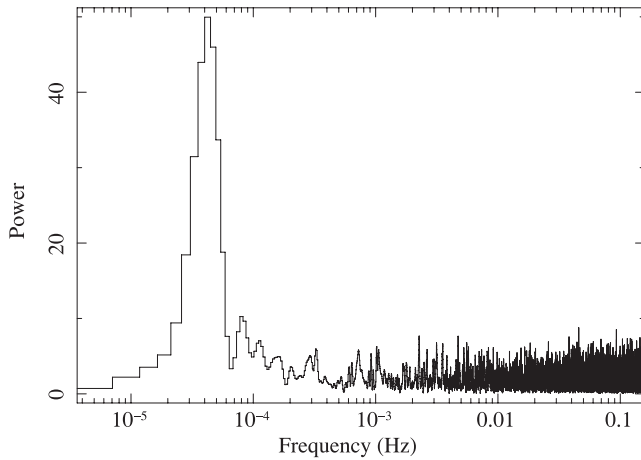


Figure 2. Average power spectrum from the three *Chandra* observations. The ~ 6.5 h ($\sim 4.26 \times 10^{-5}$ Hz) signal is apparent.

redistribution matrices for the spectral analysis were generated with ARFGEN and RMFGEN, respectively.

3 ANALYSIS AND RESULTS

3.1 Discovery of the modulation and timing analysis

CXOU J123030.3+413853 is one of the about 30 new X-ray pulsators discovered so far by the *Chandra* Timing Survey at Brera And Roma astronomical observatories project (CATS@BAR; Israel et al., in preparation; see also Esposito et al. 2013b, 2013c). CATS@BAR is aimed at the exploitation of the ACIS archival data (timed exposure imaging observations, with no gratings in use). As of 2013 May 31, approximately 8900 observations were retrieved and about 415 000 light curves were extracted. For the ~ 87 000 light curves with more than ~ 150 photons, Fourier power spectra were computed and searched for coherent or quasi-coherent signals in an automatized way by applying a detection algorithm based on that described in Israel & Stella (1996).

In the case of CXOU J123030.3+413853, a promising signal was first found in the power spectrum of the observation 4725. It showed a single high peak at the second/third Fourier frequency (depending on the assumed number of bins in the time series), corresponding to a period of ≈ 6.5 h. Considering the 8192 independent frequencies in the spectrum with frequency resolution of $\sim 1.9 \times 10^{-5}$ Hz, the detection is significant at $\sim 6.6\sigma$. When taking into account also the number of light curves searched in the CATS@BAR programme (~ 87 000), the significance of the peak is 4.7σ . In order to better investigate the signal, we used the three *Chandra* observations (Table 1) to produce a new power spectrum (Fig. 2), average of three power spectra (the power was normalized following Leahy et al. 1983 and dividing the expectation value and standard deviation of the noise distribution by the number of averaged power spectra). The peak significance increased, as expected if the signal was present in all data sets, and was estimated to be $\sim 9\sigma$.

We carefully investigated the possibility of a signal of instrumental origin. A check for spurious signals that might be introduced in the *Chandra* light curves by the spacecraft dithering, is automatically performed by the CATS@BAR signal detection pipeline. The procedure is based on the CIAO task DITHER_REGION² and

checks whether an artificial signal due to the variation of the fractional area for the given source extraction region is present in the original time series. The analysis gave a negative result: no spurious signal is present at or nearby the detected peak. As a further check, the nearby sources were searched for a similar modulation, with negative results. Finally, we notice that the CATS@BAR pipeline preserves the information (frequencies, amplitudes, etc.) related to all the detected peaks, regardless of whether they are spurious or not. As of 2013 May 31, the search produced more than 155 000 detected peaks from ~ 87 000 light curves. None of the spurious signals falls at the or close to the frequency of the peak of CXOU J123030.3+413853. We conclude that the signal (which is confirmed also by the 2008 *XMM-Newton* observation, see below) is real and intrinsic to CXOU J123030.3+413853.

We then inspected the *Chandra* and *XMM-Newton* light curves. As it can be seen from Fig. 3, the ~ 6.5 h flux modulation is rather large and clearly recognizable in the three ~ 40 ks observations (consistent flux variations are present also in the other pointings, although the short exposure times prevent an unambiguous association to the ~ 6.5 h period). In each of these observations, we measured the period by fitting a sinusoidal function to the light curve. The individual periods, (6.32 ± 0.14) h for the *Chandra*/4725 observation, (6.11 ± 0.36) h for the *Chandra*/4726, and (6.73 ± 0.38) h for the *XMM-Newton*/0556300101 (MOS data), are all consistent within the uncertainties (all errors are 1σ).

Folding the three *Chandra* observations with a common period P and looking for the value that maximizes the pulsed fraction, we obtain $P = (6.43 \pm 0.11)$ h. In Fig. 4, we show the corresponding profile obtained by folding all the *Chandra* data. The profile is slightly asymmetric, and a double-sinusoidal function provides a somewhat better fit to it than a single one ($\chi^2_\nu = 0.91$ for 11 degrees of freedom (dof) against 2.68 for 13 dof). The pulsed fraction, defined as $(M - m)/(M + m)$, where M is the maximum of the pulse profile and m the minimum, is (88 ± 6) per cent in the 0.3–8 keV band. We also show an example of soft (0.3–2 keV) and hard (2–8 keV) profiles. The pulsed fractions are compatible (84 ± 8 per cent in the soft band and 85 ± 11 per cent in the hard) and the hardness ratio between the two profiles does not significantly deviate from a constant. More in general, no statistically significant variations of the profile are observed as a function of the energy in the *Chandra* data.

3.2 Spectral analysis

For the spectral analysis (performed with the XSPEC version 12.7 fitting package; Arnaud 1996), we first concentrate on the ACIS data because, owing to the high angular resolution of the *Chandra* mirrors (~ 0.4 arcsec half-maximum) and the stable background during the exposures, they are those with the highest signal-to-noise ratio (~ 97 – 99 per cent of source counts in each observation). Given the paucity of counts, especially in the observations 1579 and 4726, we fit simple models to the three spectra simultaneously, with the normalizations free to vary and the other parameters tied up between the data sets. A power law with photon index $\Gamma \sim 1.5$ or a multicolour disc (Mitsuda et al. 1984; Makishima et al. 2000) with characteristic temperature $kT \sim 2$ keV, both modified for the interstellar absorption, provide equally good fits to the data. The best-fitting parameters are given in Table 2. The N_H value is only poorly constrained, but for both models the best-fitting value is substantially larger than the Galactic one (1.8×10^{20} cm⁻²; Dickey & Lockman 1990; Kalberla et al. 2005) and comparable with that

² See http://cxc.harvard.edu/ciao/ahelp/dither_region.html.

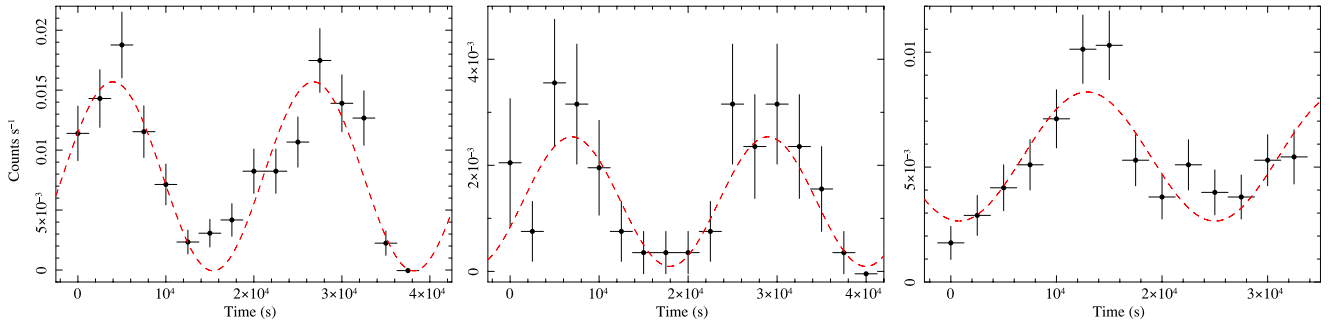


Figure 3. Background-subtracted 0.3–8 keV light curves of CXOU J123030.3+413853 from the *Chandra* 2004 July (left) and 2004 November (middle) observations and from the *XMM-Newton* 2008 May observation (right). The red dashed line shows the best-fitting sinusoidal function for each data set.

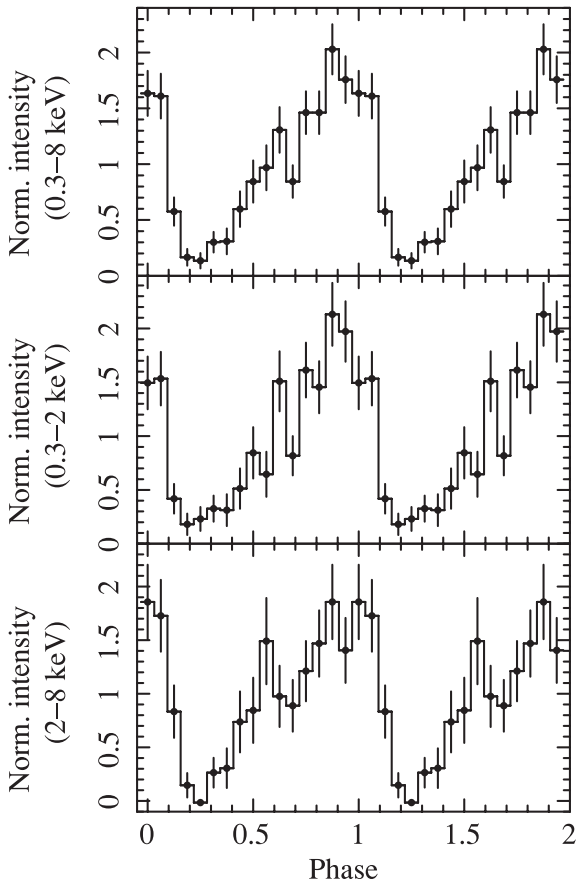


Figure 4. Background-subtracted folded profiles (from all *Chandra* observations combined) of CXOU J123030.3+413853 in the total (0.3–8 keV, top), soft (0.3–2 keV, middle) and hard (2–8 keV) energy bands.

of the point sources in NGC 4490 (Roberts et al. 2002; Gladstone & Roberts 2009).

While the fluxes measured in the first two observations (2000 November and 2004 July) are compatible, the third *Chandra* observation (2004 November) caught CXOU J123030.3+413853 at a significantly lower flux, implying a variability by a factor of ~ 5 . For a distance of 8 Mpc, the highest observed flux (obs. 4725) translates into a 0.3–10 keV isotropic luminosity of $\sim 1.1 \times 10^{39}$ erg s $^{-1}$ for the power-law fit, and of $\sim 8 \times 10^{38}$ erg s $^{-1}$ for the multicolour disc. We note that during that observation the flux at the modulation maximum was more than two times the average one, indicating an

isotropic luminosity above 10^{39} erg s $^{-1}$ (in part of the orbit) also for the multicolour disc fit.

We performed a similar analysis with the *XMM-Newton* data. After the proton flares cleaning, the net exposures were reduced in the first (second) observation to 11.2 ks (14.7 ks), 16.8 ks (22.0 ks) and 16.6 ks (23.7 ks) in the pn, MOS 1 and MOS 2 detectors, in the order given. The spectral parameters derived from the fits are consistent with those obtained from the *Chandra* observations. In both pointings, the fluxes are close to the values measured in the first two *Chandra* data sets, when the luminosity of CXOU J123030.3+413853 was about 10^{39} erg s $^{-1}$.

4 DISCUSSION

During a systematic search for new X-ray pulsators in the *Chandra* ACIS archive, we discovered a strong (~ 90 per cent pulsed fraction) modulation at about 6.4 h from the source CXOU J123030.3+413853 in NGC 4490 (a star-forming galaxy, interacting with the companion NGC 4485). This modulation is naturally interpreted as the orbital period of a binary system. The spectral analysis of the available data (three *Chandra* and two *XMM-Newton* observations between 2000 and 2008; Table 1) showed that CXOU J123030.3+413853 is a rather bright and moderately variable (within a factor of ~ 5) source, with a maximum observed luminosity exceeding 10^{39} erg s $^{-1}$.

The Eddington limit for spherical accretion of fully ionized hydrogen on to a compact object of mass M is $L_E \simeq 1.3 \times 10^{38} M/M_\odot$ erg s $^{-1}$. If CXOU J123030.3+413853 is Eddington limited, its mass should then be greater than $\sim 10 M_\odot$ (or than $\sim 5 M_\odot$ for a He or C/O donor, which is likely the case, see below), strongly arguing against a neutron star primary. In fact, it is not possible to completely rule out a neutron star on energetic grounds alone [the Eddington limit can be exceeded by a factor of a few even without invoking unusual accretion regimes, see e.g. Grimm, Gilfanov & Sunyaev 2003, and neutron-star binaries have been observed to achieve, albeit only briefly, luminosities approaching $\sim 10^{39}$ erg s $^{-1}$ (during giant outbursts in Be X-ray binary systems, see e.g. White & Carpenter 1978; Reig 2007)], but persistent sources with luminosity above a few 10^{38} erg s $^{-1}$ are clearly much easier to explain in terms of BH binaries. Moreover, the lack of breaks between $\sim 5 \times 10^{38}$ and $\gtrsim 2 \times 10^{40}$ erg s $^{-1}$ in the X-ray luminosity functions (XLFs) for point sources observed in nearby spiral galaxies suggest that above $\sim 5 \times 10^{38}$ erg s $^{-1}$ XLFs are populated mainly by X-ray binaries with BH accretors (e.g. Sarazin, Irwin & Bregman 2000; Gilfanov 2004; Kim & Fabbiano 2004; Fabbiano 2006; Ivanova & Kalogera 2006). We thus believe that a BH is indeed the most probable

Table 2. *Chandra* and *XMM-Newton* spectral results. Errors are at a 1σ confidence level for a single parameter of interest.

Model ^a	Obs. ID	N_{H}^b (10^{21} cm^{-2})	Γ	kT (keV)	Observed flux ^c ($10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$)	Luminosity ^d ($10^{38} \text{ erg s}^{-1}$)	χ^2_{ν} (dof)
<i>Chandra</i>							
PHABS*POWERLAW	1579				$8.4^{+0.9}_{-1.0}$	9.3 ± 0.9	
	4725	3.5 ± 1.5	1.5 ± 0.2	–	10.0 ± 0.9	11.1 ± 0.8	0.89 (20)
	4726				$1.8^{+0.4}_{-0.3}$	$2.0^{+0.4}_{-0.3}$	
PHABS*DISKBB	1579				7.8 ± 1.0	$6.8^{+1.0}_{-0.6}$	
	4725	$1.1^{+1.1}_{-1.0}$	–	$1.9^{+0.4}_{-0.3}$	$9.0^{+1.0}_{-0.8}$	$7.9^{+0.9}_{-0.7}$	0.86 (20)
	4726				$1.6^{+0.4}_{-0.3}$	$1.4^{+0.3}_{-0.2}$	
<i>XMM-Newton</i>							
PHABS*POWERLAW	0112280201	$4.5^{+1.8}_{-1.5}$	$1.8^{+0.2}_{-0.3}$	–	$7.1^{+1.2}_{-1.0}$	$8.9^{+1.1}_{-1.0}$	0.81 (16)
	0556300101				7.7 ± 0.8	$9.6^{+1.2}_{-1.0}$	
PHABS*DISKBB	0112280201	$1.8^{+1.2}_{-1.0}$	–	$1.4^{+0.3}_{-0.2}$	$6.4^{+1.0}_{-0.9}$	$5.7^{+0.9}_{-0.7}$	0.80 (16)
	0556300101				7.0 ± 0.8	6.3 ± 0.6	

^aXSPEC model.^bThe abundances used are those of Wilms, Allen & McCray (2000). Essentially identical values are obtained with the abundances by Lodders (2003) and Asplund et al. (2009), while values ~ 30 per cent lower are derived with those of Anders & Grevesse (1989). The photoelectric absorption cross-sections are from Balucinska-Church & McCammon (1992).^cIn the 0.3–8 keV energy range.^dIsotropic 0.3–10 keV luminosity, calculated from the unabsorbed flux assuming a distance of 8 Mpc.

primary for CXOU J123030.3+413853, and in the following we will discuss the source in this context.

4.1 The nature of the binary system

The X-ray periodicity of 6.4 h indicates an orbital modulation and, considering the high X-ray luminosity, there are two possibilities for the source nature: either a low-mass (LMXB) or a high-mass X-ray binary (HMXB). While the 0.3–10 keV spectral distribution is compatible with both kinds of X-ray binaries, the timing analysis (orbital period and morphology of the orbital light curve) discloses more information on the source nature.

In the first hypothesis, an orbital period of 6.4 h is typical of an LMXB with a late-spectral-type main-sequence companion (Verbunt 1993). Eclipsing and/or dipping LMXBs with similar orbital periods (e.g., MXB 1659–298, with $P_{\text{orb}} = 7.11$ h; Cominsky & Wood 1984) display X-ray emission periodically modulated by the presence of X-ray eclipses produced by the low-mass companion in a high-inclination system ($i > 70^\circ$; e.g. Frank, King & Lasota 1987), and/or by the presence of dips due to the obscuration produced by the accreting matter located in the disc bulge (see Díaz Trigo et al. 2006 for a review). However, in the so-called dippers, the X-ray minima are typically much sharper than what shown by CXOU J123030.3+413853 and, in any case, the morphology of the source light curve is very different. Moreover, dippers usually show energy-dependent X-ray emission, since the periodic modulation is produced by absorption of X-rays by the (neutral and ionized) matter into the line of sight, contrary to what we observed in CXOU J123030.3+413853.

A smoother modulation in the X-ray light curve of an LMXB can be produced in a so-called accretion disc corona (ADC) source: the X-ray emission in this kind of X-ray binaries viewed edge-on is mostly blocked by the dense, obscuring, outer edge of the accretion disc. The presence of an extended corona scatters into the line of sight the X-ray emission coming from the central obscured source, so that the outer edge of the dense disc modulates this scattered

X-ray emission, producing an observed orbital X-ray light curve with a very smooth profile (Mason & Cordova 1982). The prototype of the ADC sources is X 1822–371, a neutron star LMXB with an orbital period of 5.57 h (e.g. Somero et al. 2012 and references therein). However, the profile morphology in ADC sources, although much smoother than in other eclipsing or dipping LMXBs, is again very different from that of CXOU J123030.3+413853. To summarize, the hypothesis that CXOU J123030.3+413853 is an LMXB seems to be unlikely, also because LMXBs containing BHs are usually transient X-ray sources, with outburst durations of the order of weeks to months (e.g. Remillard & McClintock 2006), whereas CXOU J123030.3+413853 is persistent, although variable within a factor of 5 (see Table 2).

A viable alternative is that CXOU J123030.3+413853 is an HMXB. Given its short orbital period, both a main-sequence and a supergiant early-type companion cannot fit into the very narrow orbit. The remaining possibility is that the source is a late evolutionary product of an HMXB, hosting a Wolf–Rayet (WR) star (see Crowther 2007 for a review on WR stars), similar to Cyg X–3 (Giacconi et al. 1967).

Cyg X–3 is a bright X-ray binary ($L_X \approx 10^{38} \text{ erg s}^{-1}$) that shows an even shorter orbital period of 4.8 h (Canizares et al. 1973) and a remarkably similar orbital asymmetric X-ray light curve, with a slow rise and a fast decline (Zdziarski et al. 2012). Cyg X–3 is a unique source in our Galaxy, being the only X-ray binary containing a WR star (van Kerkwijk et al. 1996). The nature of the compact object accreting from the WR wind is still unclear, although there are many indications (radio, infrared and X-ray emission properties; Szostek & Zdziarski 2008; Szostek, Zdziarski & McCollough 2008) pointing to a 2–5 M_\odot BH (see e.g., Zdziarski, Mikołajewska & Belczyński 2013), as also suggested by evolutionary models (Lomen et al. 2005; Belczyński et al. 2013). The peculiar shape of the Cyg X–3 orbital X-ray light curve and its remarkable energy independence received attention since early 1970s (e.g. Hertz, Joss & Rappaport 1978 and references therein), and they were explained by transfer of X-rays through a ‘cocoon’, a cloud of scattering medium.

A more recent study of the orbital modulation of X-rays in Cyg X–3 was performed by Zdziarski, Misra & Gierliński (2010), finding that the X-ray modulation can be produced by both absorption and Compton scattering in the WR stellar wind (the minima being accounted for by the highest optical depth at the superior conjunction). In CXOU J123030.3+413853, the shape of the orbital profile indicates an asymmetry in the scattering matter. This anisotropy is likely due to either a WR wind focused towards the compact object or a cloud of ionized matter associated with a bulge in the accretion disc, probably produced by the gravitationally focused stellar wind colliding with the outer accretion disc. Additional contribution by a jet from the putative BH is a possibility. Eclipses by the companion star can be smoothed out by Compton scattering with high optical depth (see e.g. Hertz et al. 1978). The effect of photoelectric absorption of soft X-rays in the WR wind can be reduced by the possible presence of a soft excess due to reemission of the absorbed continuum by the WR stellar wind. So, several contributions are possible which could modulate the X-ray emission along the orbit, similar to the luminous Galactic source Cyg X–3.

WR–BH binary systems are very rare. Apart from Cyg X–3, for which the nature of the compact object is still unclear, only two such systems are known to date, both in external galaxies. One is located in the dwarf irregular galaxy IC 10 (IC 10 X–1; Bauer & Brandt 2004; Prestwich et al. 2007) and the other in the spiral NGC 300 (NGC 300 X–1; Carpano et al. 2007a,b). In these two sources, the orbital periods are much larger than in CXOU J123030.3+413853, exceeding 30 h (Prestwich et al. 2007; Crowther et al. 2010).³ So, CXOU J123030.3+413853 could be a candidate extragalactic twin to Cyg X–3, as well as one of the very few WR–BH binary systems known in the local Universe. The interest in the systems of this kind, besides their rarity, is also due to the fact that they might be the progenitors of a double-BH binary (Lommen et al. 2005; Bulik, Belczynski & Prestwich 2011).

4.2 A transitional object between BH X-ray binaries and ULXs

As mentioned above, in at least one of the *Chandra* observations, the luminosity of CXOU J123030.3+413853 marginally crosses the conventional luminosity threshold of 10^{39} erg s^{–1} and may then be defined as a ‘borderline’ ULX. Other variable (and persistent) X-ray sources in nearby galaxies show large excursions in luminosity and enter only at times the low-luminosity ULX regime (e.g. NGC 253 X–1; Pintore et al., in preparation). In addition, a few transient ULXs, with luminosities at maximum slightly above 10^{39} erg s^{–1}, have also been identified (e.g. Sivakoff et al. 2008; Middleton et al. 2012, 2013; Soria et al. 2012; Esposito et al. 2013a). At low luminosities, some of these sources show properties consistent with those of more conventional X-ray binaries. Interestingly, at least one of the transient ULXs in M 31 was identified with an LMXB (Middleton et al. 2012), while CXOU J123030.3+413853 is likely accreting from a WR star (see Section 4.1), consistent with the persistent character of the source. The existence of these transitional objects is clearly very interesting because they reveal how the properties of BH binaries evolve entering the ULX regime.

CXOU J123030.3+413853 is particularly interesting in this respect because it shows evidence of an orbital periodicity, detected only in a handful of ULXs (Kaaret & Feng 2007; Liu, Bregman & McClintock 2009; Zampieri et al. 2012), which may make it possible to extract additional physical information about the system.

The observed X-ray spectra of CXOU J123030.3+413853 do not have sufficient counting statistics to discriminate among different models and are broadly consistent with several interpretations. The power-law fit gives spectral indices reminiscent of the hard state of Galactic BH binaries, but at the same time the DISKBB fits give temperatures consistent with those of the soft state. In general, the spectra appear slightly harder than those of other low-luminosity ULXs (e.g. Stobbart, Roberts & Wilms 2006; Berghea et al. 2008). However, higher counting statistics observations are needed to better constrain the spectral properties and understand if the source may show spectral signatures and/or transitions similar to those typically observed in brighter ULXs (Gladstone, Roberts & Done 2009; Kajava & Poutanen 2009; Pintore & Zampieri 2012). Assuming that at peak the source is in a soft/disc dominant state and using the normalization K of the *Chandra* DISKBB fit, it is possible to estimate the BH mass as (Lorenzin & Zampieri 2009)

$$M \approx 12.5 \left(\frac{D}{1 \text{ Mpc}} \right) \left(\frac{K}{\cos i} \right)^{1/2} M_{\odot},$$

where i is the inclination angle ($i = 0^{\circ}$ corresponds to a face-on disc). For CXOU J123030.3+413853 (obs. 4725), one gets $M \approx 2.8 (D_8 / \sqrt{\cos i}) M_{\odot}$ (where D_8 is the distance to the source in units of 8 Mpc). If $i > 30^{\circ}$, which is likely, given the strong X-ray orbital modulation, the above relation implies $M > 3 M_{\odot}$. As mentioned above, if at maximum the source is also radiating at a fraction ($\lesssim 0.5$) of the Eddington luminosity, this would lead to a BH mass $M > 5\text{--}10 M_{\odot}$ (for a He or C/O WR star). Therefore, the compact object is consistently inferred to be a BH, although the presently available data do not allow us to further constrain its mass. However, having detected a modulation interpreted as the orbital period of the system, CXOU J123030.3+413853 becomes a good candidate for searching the optical counterpart and for attempting direct dynamical measurements of the BH mass (e.g. IC 10 X–1; Prestwich et al. 2007; Silverman & Filippenko 2008).

Transient ULXs and objects like CXOU J123030.3+413853 show that the populations of bright X-ray binaries and low-luminosity (a few 10^{39} erg s^{–1}) ULXs may be smoothly connected, with borderline objects and sources transiting from one class to the other depending on the varying accretion rate. However, only sources with relatively massive BHs and/or crossing the Eddington limit may become bright (isotropic $L_X \gtrsim 10^{40}$ erg s^{–1}) ULXs and show the typical spectral signatures related to the ultraluminous regime (Gladstone et al. 2009; Pintore et al., in preparation).

Bright HMXBs and ULXs appear to be preferentially associated to low-metallicity, star-forming environments (e.g. Grimm et al. 2003; Mapelli et al. 2010, 2011a). As discussed in the next section, NGC 4490 has both a low metallicity and a high star formation rate (SFR). Besides the transitional object CXOU J123030.3+413853, it contains other eight sources catalogued as ULXs (Roberts et al. 2002; Winter et al. 2006; Fridriksson et al. 2008; Gladstone & Roberts 2009; Yoshida et al. 2010). The detected number of sources and the HMXB nature of CXOU J123030.3+413853 are consistent with theoretical expectations based on the properties of the environment.

³ It is interesting to note that IC 10 X–1 and NGC 300 X–1 are among the most massive stellar-mass BHs for which dynamical mass constraints are available (Özel et al. 2010). The most probable mass of NGC 300 X–1 is $\approx 20 M_{\odot}$ (Crowther et al. 2010), while that of IC 10 X–1 is $\approx 33 M_{\odot}$ (Prestwich et al. 2007; Silverman & Filippenko 2008).

4.3 CXOU J123030.3+413853 and its environment

NGC 4490 is a star-forming, interacting galaxy. An estimated average SFR of $5.5 M_{\odot} \text{ yr}^{-1}$ can be obtained from H α (assuming the calibration by Kennicutt et al. 1987, and an extinction of ≈ 1 mag; Clemens et al. 1999). The companion galaxy, NGC 4485, is connected with NGC 4490 by an evident optical bridge. Previous studies (Roberts et al. 2002; Fridriksson et al. 2008; Gladstone & Roberts 2009; Yoshida et al. 2010) found eight ULXs in the NGC 4485/4490 complex. CXOU J123030.3+413853 probably was not included in this sample of ULXs because its luminosity is borderline and variable.

Smith et al. (2012, and references therein) suggest an enhancement (by a factor of 2–4) of the number of ULXs in interacting galaxies. On the other hand, NGC 4485/4490 nicely follows the correlation between SFR and ULX number (Mapelli et al. 2010, see also Grimm et al. 2003; Ranalli, Comastri & Setti 2003; Mineo, Gilfanov & Sunyaev 2012): for an SFR of $\approx 5.5 M_{\odot} \text{ yr}^{-1}$, we expect 6^{+6}_{-3} ULXs, fairly consistent with the observed number of eight or nine (with CXOU J123030.3+413853) ULXs.

CXOU J123030.3+413853 is close to the tail that connects NGC 4490 with the smaller companion NGC 4485, but is neither in a star-forming region nor close to a young star cluster (as it appears from the Sloan Digital Sky Survey Data Release 7 data base; Abazajian et al. 2009). A large fraction of HMXBs and ULXs were found to be offset with respect to the closest star-forming region and/or young star cluster (e.g. Zezas et al. 2002; Kaaret et al. 2004; Berghea 2009; Poutanen et al. 2013). The most likely explanation is that a number of X-ray binaries were ejected from the parent star cluster as a consequence of either supernova kick or dynamical interaction (e.g. Gualandris et al. 2005; Fragos et al. 2009; Mapelli et al. 2011b; Repetto, Davies & Sigurdsson 2012).

Finally, NGC 4490 has relatively low metallicity ($12 + \log(\text{O}/\text{H}) \approx 8.3\text{--}8.4$, corresponding to $Z \approx 0.25 Z_{\odot}$, assuming $Z_{\odot} = 0.02$; Pilyugin & Thuan 2007). Recent studies (e.g. Mapelli, Colpi & Zampieri 2009; Mapelli et al. 2010, 2011a; Kaaret & Feng 2013; Prestwich et al. 2013) indicate that ULXs and bright HMXBs tend to prefer metal-poor environments. The low metallicity of NGC 4490 fairly confirms this behaviour (NGC 4485/4490 was already included in the galaxy sample by Mapelli et al. 2010). The anticorrelation between ULXs and metallicity has been attributed either to the fact that more HMXBs can form at low metallicity (e.g. Linden et al. 2010), or that the mass of BHs can be higher in metal-poor environments (e.g. Zampieri & Roberts 2009; Belczynski et al. 2010; Mapelli et al. 2013). Thus, constraining the mass of the BH candidate in CXOU J123030.3+413853 would provide an important clue to understand the metallicity–HMXB connection.

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