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A new candidate Wolf–Rayet X-ray binary in NGC 253

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ABSTRACT

We have discovered a persistent, but highly variable X-ray source in the nearby starburst galaxy NGC 253. The source varies at the level of a factor of about 5 in count rate on time-scales of a few hours. Two long observations of the source with *Chandra* and *XMM–Newton* show suggestive evidence for the source having a period of about 14–15 hours, but the time sampling in existing data is insufficient to allow a firm determination that the source is periodic. Given the amplitude of variation and the location in a nuclear starburst, the source is likely to be a Wolf–Rayet X-ray binary, with the tentative period being the orbital period of the system. In light of the fact that we have demonstrated that careful examination of the variability of moderately bright X-ray sources in nearby galaxies can turn up candidate Wolf–Rayet X-ray binaries, we discuss the implications of Wolf–Rayet X-ray binaries for predictions of the gravitational wave source event rate, and, potentially, interpretations of the events.

Key words: stars: Wolf–Rayet – galaxies: individual: NGC 253 – galaxies: starburst – X-rays: binaries.

1 INTRODUCTION

Wolf–Rayet X-ray binaries are a subclass of high-mass X-ray binaries where the donor star is a Wolf–Rayet star, rather than an ordinary high-mass star. These systems present two golden opportunities to study extreme physics using binary stars that are not seen in most other classes of X-ray binaries. First, the archetypal Wolf–Rayet X-ray binary, Cygnus X-3 (see e.g. van Kerkwijk et al. 1996), is also the first clear example of an accretion-powered stellar mass system that produces high-energy gamma-rays (Tavani et al. 2009), with the prevailing interpretation being that the system is a strong high-energy emitter due to interactions between its jet and its strong stellar wind (e.g. Dubus, Cerutti & Henri 2010).

Secondly, Wolf–Rayet X-ray binaries represent one of the best candidate sources of gravitational wave source progenitors in the Universe (e.g. Belczyński et al. 2013). As systems with orbital periods of $\lesssim$1 d, they are more robust to remaining bound after the second supernova than are very wide high-mass X-ray binaries. They may thus lead to double black holes with merger time-scales shorter than a Hubble time, meaning that detection of these systems can give real insight into the expected rate of mergers to be seen with experiments like Advanced LIGO (Belczyński et al. 2013).

To date, there are three convincing candidate Wolf–Rayet X-ray binaries known – Cygnus X-3 (van Kerkwijk et al. 1996), NGC 300 X-1 (Carpano et al. 2007), and IC 10 X-1 (Bauer & Brandt 2004; Clark & Crowther 2004). There is also a fourth object, SS 433, which has sometimes been suggested to be a Wolf–Rayet X-ray binary, but which is more likely to be mimicking such a system due to a strong disc wind (Fuchs, Koch Miramond & Abraham 2006). It is, however, worth remembering that these systems are quite short-lived, so that for every one we see, many more have likely been formed and died in the past. Thus while these objects may be rare, they may still represent an extremely important progenitor channel for the formation of double black hole and black hole/neutron star binary systems which may merge on a Hubble time. In this paper, we report the discovery of a new candidate Wolf–Rayet X-ray binary in the galaxy NGC 253, and discuss its implications for understanding the double compact object merger rate. We note that in this paper, we take the term Wolf–Rayet star to mean any massive star which has completely lost its hydrogen envelope. We note that some authors use a more restrictive definition, which distinguishes between Wolf–Rayet stars and other classes of naked helium stars based on details

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Table 1. The observations used for this project – the columns are the start date for the observation; the start time for the observation, the exposure time, the satellite used, and the Observation ID number.

Observation	Date	Start time	Exp. time (s)	Satellite	ObsID
A	1999 December 16	12:11:02	13 990	*Chandra*	969
B	1999 December 27	2:19:05	43 610	*Chandra*	790
C	2000 June 3	5:15:36	60 809	*XMM–Newton*	0125960101
D	2000 June 4	5:07:01	17 509	*XMM–Newton*	0125960201
E	2000 December 14	09:00:02	33 732	*XMM–Newton*	011900101
F	2003 June 20	08:13:24	140 799	*XMM–Newton*	0152020101
G	2003 September 19	12:50:20	82 550	*Chandra*	3931
H	2005 December 16	20:14:55	23 211	*XMM–Newton*	0304851101
I	2006 January 2	7:46:27	11 811	*XMM–Newton*	0304850901
J	2006 January 6	4:12:06	11 846	*XMM–Newton*	0304851001
K	2006 January 9	18:46:09	19 918	*XMM–Newton*	0304851201
L	2006 January 11	1:59:10	20 916	*XMM–Newton*	0304851301
M	2012 September 2	5:59:52	19 720	*Chandra*	13830
N	2012 September 18	3:37:53	19 720	*Chandra*	13831
O	2012 November 16	1:04:25	19 720	*Chandra*	13832

of optical and infrared spectroscopy – see e.g. Linden, Valsecchi & Kalogera (2012) and references within for a further discussion.

The structure of this paper is as follows: in Section 2, we present a discussion of the observations used and the data analysis methodology; in Section 3, we discuss the results of the X-ray data analysis; in Section 4, we discuss the interpretation of this object as a Wolf–Rayet X-ray binary; in Section 5, we outline a framework for converting detected Wolf–Rayet binaries into compact object merger rates; and in Section 6, we summarize our conclusions.

2 OBSERVATIONS AND DATA ANALYSIS

We examined all public observations of NGC 253 from *Chandra* and *XMM–Newton* for which the integrations are longer than 5000 s of exposure time, and we also used three proprietary *Chandra* observations from 2012. The data are summarized in Table 1. In this section, we discuss which data are used, and the procedures used for the analysis, while in the next section, we discuss the specific results.

This project began with the discovery of a strongly variable source, CXOU J004732.0−251722.1, in the proprietary *Chandra* observations taken in 2012 (observations M–O in Table 1). Following that discovery, we examined the data from the other available X-ray observations, in order to see if that variation was usual, and if a period could be identified.

2.1 *Chandra* data analysis

The *Chandra* observations from before 2004 were all obtained with ACIS-S, while those from 2012 were obtained with ACIS-I. The data were analysed using the Chandra Interactive Analysis of Observations (CIAO) software, version 4.3. The extraction region used is a 2.5 arcsec circle centred on CXOU J004732.0−251722.1. We used a 2–7 keV bandpass for *Chandra* because the lower energies are heavily affected by diffuse emission from gas in NGC 253 itself. The *Chandra* image, along with the *XMM–Newton* images, from the respective longest exposures, are show in Fig. 1.

2.2 *XMM–Newton* data analysis

In order to check if similarly large variations from CXOU J004732.0−251722.1 had been detected in previous *XMM–Newton* observations of NGC 253, the longest individual exposure was selected: ObsID 0152020101 was taken in 2003 June, and lasted about 141 ks. Those data were taken in Full Frame mode, with the medium filter for the MOS, and the thin filter for the pn. The data were reduced using the *XMM–Newton* Science Analysis Software (SAS) version 12.0.1, with standard parameters and methods. After data reduction, exclusion of the intervals affected by high particle background thanks to the application of the appropriate good time intervals (GTIs), and selection of the energy range of interest (0.2–10.0 keV), the exposure time was reduced to about 110 ks.

The *XMM–Newton* light curves for CXOU J004732.0−251722.1 were extracted from the three detectors (MOS1, MOS2, and pn) using a circular aperture with a diameter of 5 arcsec and centred on the best position derived from the *Chandra* data. We note that this region is much smaller than the point spread function (PSF) of *XMM–Newton* (encompassing roughly 30 per cent of the photons emitted by the source for the pn, and about 40 per cent for the MOS). The 5 arcsec diameter was chosen to maximize the fraction of PSF included while minimizing contamination from the numerous nearby sources; any larger radius would start to include unrelated emission from the nucleus. All *XMM–Newton* light curves presented in this paper were corrected for background, using an extraction region located far from the nucleus. Finally, the source light curves are corrected for various effects affecting the detection efficiency and for effects affecting the stability of the detection within the exposure using the EPICLCCORR tool; this correction accounts for the PSF effects.

We note that the extraction region chosen is relatively small compared to the pixel size of the *XMM–Newton* instruments (1.1 arcsec for the MOS, 4.1 arcsec for the pn). However, the events generated by the SAS are randomly re-distributed over the instrument pixel into sub-pixels of 0.05 arcsec. Spatial coordinates are always randomized to avoid Moiree patterns. Thus, extracting the photons from a small region leads to correct data products (i.e. spectra and light curves) thanks to the randomization process and the use of sub-pixels, regardless of the position of that extraction region inside the natural instrument pixel. Of course, all images produced from those event lists are rebinned to match the physical detector pixel sizes.

The *Chandra* and *XMM–Newton* pn light curves are presented in Fig. 2. The MOS data have lower signal-to-noise ratio because of their smaller collecting areas than the pn, and poorer background

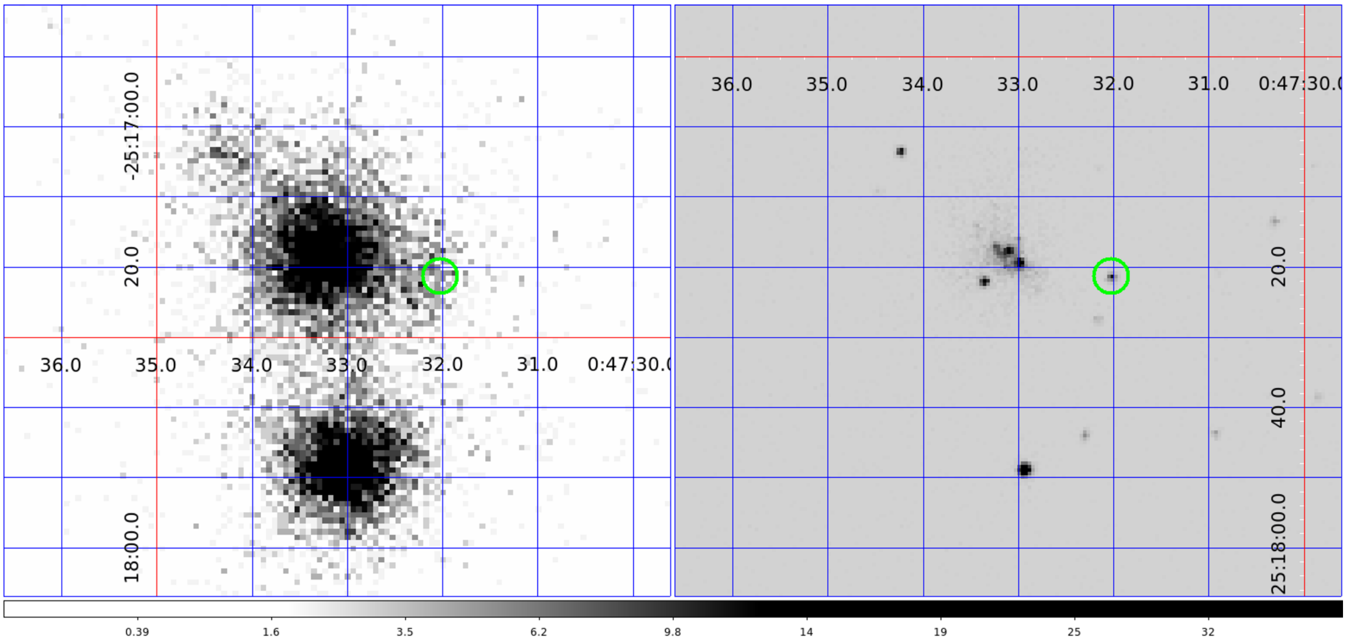

Figure 1. Left: the *XMM* image of the same region, with the WCS matched between the two images, taken during observation 0152020101 (Observation F). Right: the *Chandra* image from observation 3931 of the candidate Wolf–Rayet X-ray binary (Observation G). The green circle has a 2.5 arcsec radius around the brightest pixel of the Wolf–Rayet binary candidate. Both images show photons from 2 to 7 keV. Of particular importance to note is that there is no strong extended structure in the *Chandra* image near the position of the bright source, so that any emission there must be from point sources. The images have been cleaned to remove flaring background periods.

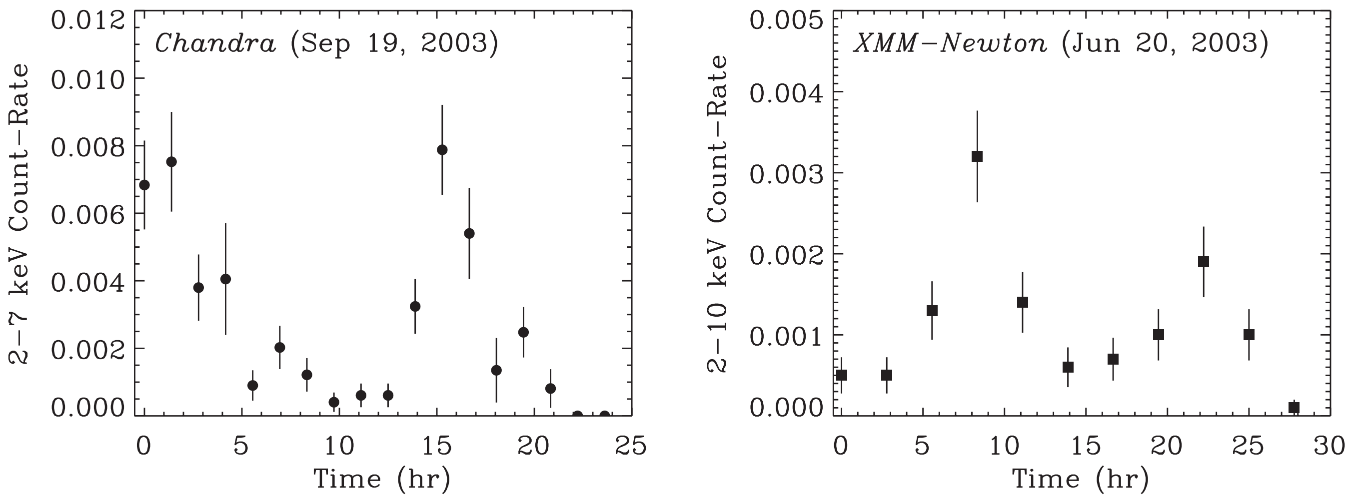

Figure 2. Left: the *Chandra* light curve for the source. Right: the *XMM–Newton* pn light curve for the source.

subtraction than *Chandra*, but show results consistent with those from the pn data. The MOS data are shown in Fig. 3.

3 RESULTS

Some early results for our *Chandra*-NuSTAR observations of NGC 253, focused on its variable nucleus, have already been reported in Lehmer et al. (2013). Our analysis of the *Chandra* data taken during 2012 for that project shows CXO J004732.0−25172.1 with about 100 source counts on September 2, 60 source counts on September 18, and an upper limit of 8 source counts on November 16, with all counts reported in the 2–7 keV band. The location of the source, in J2000 coordinates, at right ascension of 0:47:32.0 and declination of −25: 17: 22.1 is 17 arcsec from the centre of NGC 253 (Veron-Cetty & Veron 2010).

Given this unusually fast variability, we examined the older observations of the source to determine whether it was a transient. We found it to be bright in several past observations. We then examined its intra-observation variability in the two longest observations – F and G in Table 1. The source count rate varies by a factor of about 8 on time-scales of a bit more than half a day (see Fig. 2). The nature of the variability is suggestive of a periodic system with a large amplitude of variability, but given that fewer than two cycles are seen if the source is periodic, no definitive statement can be made on the basis of the *Chandra* data alone.

We next extracted light curves with 5000 second binning from all the observations and computed a Lomb–Scargle (Lomb 1976;

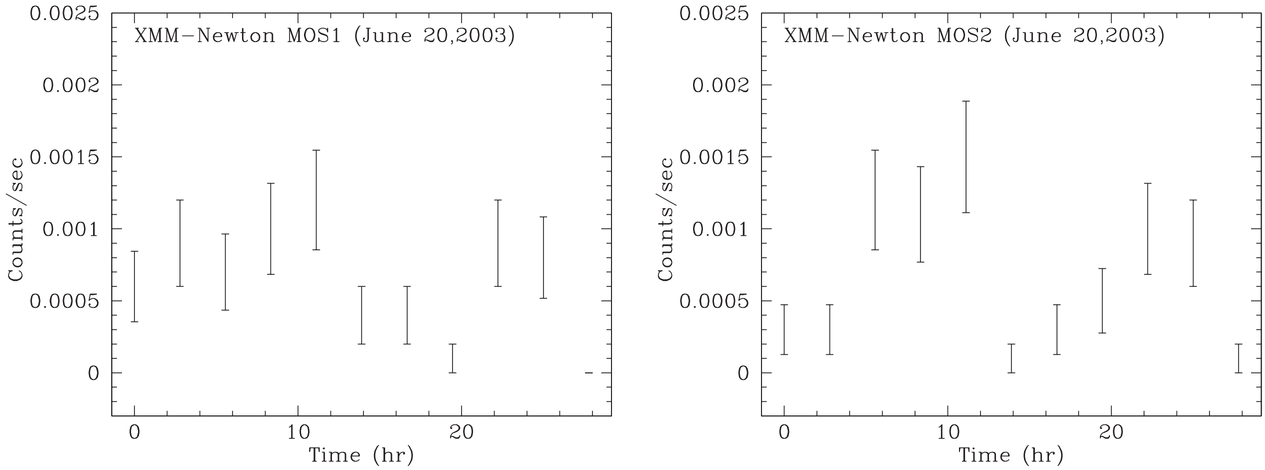

Figure 3. The EPIC MOS light curves for observation 0152020101 (i.e. the same observation for which the pn light curve is plotted in Fig. 2). One can clearly see that the peaks and troughs in the light curve are in the same places as for the PN light curve.

Scargle 1982) periodogram of the data. The strongest candidate periodicity is at 7.57 h, which may be either the first harmonic of the period, or an alias of the first harmonic. It might be expected that the harmonics of the period will be stronger than the fundamental in a periodogram because the light curve does not appear to be sinusoidal. No strong signal, however, is found at 15.04 h, arguing that if the signal at 7.57 h is the real first harmonic, that an alias of the fundamental is much stronger than the fundamental itself. The poor sampling of the data makes it difficult to establish any of the weaker peaks in the data as a genuine periodicity. More data, with a sampling pattern more appropriate to the expected 14–15 h period, are needed in order to establish clearly whether the source is strictly periodic, and what the period is. We also note that we searched the NuSTAR data at the source position for possible periodicities as well, but found only periods and aliases of periods related to the satellite orbit.

A natural explanation for a recurrent transient in a young stellar population (which the central region of NGC 253, being a starburst, is) would be for it to be a Be X-ray binary. However, the candidate period of about 15 h is far too long to be a neutron star pulse period, and far too short to be the orbital period for a Be X-ray binary (i.e. a system with a neutron star or black hole accreting from the equatorial wind of a Be star). The orbital periods of Be X-ray binaries tend to be a few months, and their frequent, Type I, outbursts tend to last about 0.2–0.3 orbital periods, and to peak at no more than about 10^{37} erg s^{-1}, while their less frequent Type II outbursts tend to show smooth light curves on time-scales of days (see e.g. Reig & Nespoli 2013). In detail, then, the system's light curve does not resemble that of a Be X-ray binary, and some alternative form of highly variable source that can exist in a young stellar population is needed. The candidate period and the large amplitude of variability are in line with the empirical results from known Wolf–Rayet X-ray binaries (e.g. Bauer & Brandt 2004; Carpano et al. 2007).

3.1 The X-ray spectrum

Given that the source has relatively few counts, detailed X-ray spectroscopy cannot be done. The 2003 September 19 observation has the largest total number of counts within 2.5 arcsec – the *XMM–Newton* observations would normally provide better spectroscopy than the *Chandra* observations, but for this case, only the core of the PSF can be used for the *XMM–Newton* data analysis, due to the crowding near the source location.

We extract the *Chandra* spectrum of the source using the CIAO SPECEXTRACT tool and a 2.5 arcsec source region, and group the channels into bins of at least 15 counts per channel. We also use an off-source background region, centred at RA of 00:47:37.1 and Dec. of -25:17:08.9, with a radius of 29 arcsec. The background region was chosen to be at a similar surface brightness to the region around our source of interest while also not including any bright sources. Because there are too few counts in the source-free parts of the local background region to make a local background estimate, there will remain the possibility that the spectral fits are affected by the detailed shape of the background spectrum. We first fit the spectra from 0.5 to 7.0 keV, accounting for the full range over which there are many counts and the *Chandra* response matrix is well-calibrated, and then repeat the fits from 2.0 to 7.0 keV to minimize the effects from contamination from the diffuse background – given the moderate number of total counts, we believe this is the most robust way to handle the possibility of an unusual local background.

We consider several spectral models. First we consider two of the simplest models commonly used to fit the spectra of accreting sources – a power law and a disc blackbody (Mitsuda et al. 1984). In both cases, the foreground absorption is fixed to the Galactic column density of 1.4×10^{20} cm^{-2} (Dickey & Lockman 1990). We use the phabs component in XSPEC to describe the absorption. In both cases, the fit is formally unacceptable, and produces physically unlikely parameter values – for the power law, the photon index Γ is 0.45 and $\chi^2/\nu = 45.2/23$. For the disc blackbody, the inner disc temperature is 17.2 keV and $\chi^2/\nu = 51.0/23$. Uncertainties cannot be computed within XSPEC for sources with $\chi^2/\nu > 2$, so these values are presented without error bars. The source has 394 counts from 0.5 to 7.0 keV and 265 counts in the 2–7 keV energy range.

This is perhaps not surprising, since there is likely to be additional absorption both by the wind of the donor star and by the interstellar medium of NGC 253. We then re-fit the spectrum with the same two models, allowing $N_{\rm H}$ to float freely. For the disc blackbody we find $N_{\rm H} = 8.0^{+0.37}_{-0.30} \times 10^{21}$ cm^{-2}, $k_{\rm B}T = 2.2^{+1.4}_{-0.6}$ keV, with $\chi^2/\nu = 25.5/22$, and hence a null hypothesis probability of 0.27. For the power law, we find $N_{\rm H} = 1.0^{+0.5}_{-0.4} \times 10^{22}$ cm^{-2} and $\Gamma = 1.37^{+0.45}_{-0.41}$, with $\chi^2/\nu = 28.2/22$, so there is a null hypothesis probability of 0.17. The 90 per cent confidence interval is given for all parameters.

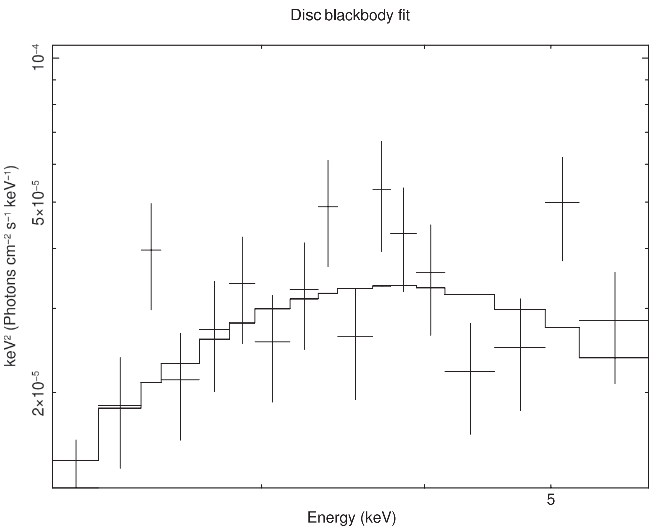

Figure 4. The unfolded spectrum of our candidate Wolf–Rayet X-ray binary, fitted with a disc blackbody model. One can see that the model describes the data well, and that more sophisticated models are unlikely to be well constrained given the quality of the data.

When fitting from 2 to 7 keV, the power-law best-fitting values are $N_{\rm H} = 5.6^{+3.3}_{-2.7} \times 10^{22}\,{\rm cm}^{-2}$ and $\Gamma = 3.4^{+1.4}_{-1.2}$, with $\chi^2/\nu = 17.0/14$, so there is a null hypothesis probability of 0.26, and the disc blackbody fits yield $N_{\rm H} = 3.1^{+2.2}_{-1.9} \times 10^{22}\,{\rm cm}^{-2}$, $k_{\rm B}T = 1.2^{+0.7}_{-0.3}$ keV, with $\chi^2/\nu = 18.1/14$, and hence a null hypothesis probability of 0.20. The absorption columns are marginally larger than those inferred for the fits including the 0.5–2.0 keV band. The disc blackbody model, which we regard as the most likely of the bunch for reasons discussed below, is plotted in Fig. 4.

While these models are not likely to provide full descriptions of the data, given the variability, regardless of the interpretation, more detailed modelling is not justified by the data. One broad conclusion is well-justified by the data – that significant foreground absorption in excess of the Galactic foreground is required. Beyond this, the results for the fits made from 2 to 7 keV argue mildly for the source to be a black hole in a canonical soft state (i.e. a disc blackbody with $k_{\rm B}T \sim 1$ keV), rather than a black hole in a hard state (a power law with $\Gamma \sim 1.5$–1.7) or a high magnetic field accreting X-ray pulsar (a power law with $\Gamma \sim 0.5$–1.0), because the parameter values for the soft state black hole case fit well to the data, while the fitted parameter values do not match those expected for the other two cases. Also, the model for the disc blackbody model corresponds to an unabsorbed flux of 1.4×10^{-13} erg s^{-1} cm^{-2} from 0.5 to 8 keV, which gives a luminosity of 1×10^{38} erg s^{-1}. Such a luminosity is a reasonable luminosity to expect for a soft state black hole, but it would be unusual for a hard state black hole, assuming that the black hole mass is about 10 M$_\odot$. The typical state transition luminosities between the hard state and soft states for black holes typically occur at about 2 per cent of the Eddington luminosity (Maccarone 2003), with only short-lived hard states which are brighter and occur during outbursts as a hysteresis effect (Maccarone & Coppi 2003).

We also consider the possibility that the source has a neutron star accretor with a low magnetic field, and hence behaves like the Galactic ‘Z-sources’ – the low magnetic field neutron stars accreting near the Eddington rate. We take a single example of a spectrum of the Z-source LMC X-2 from Lavagetto et al. (2008) and determine whether the model is consistent with the data for this source. We use the parameter values for the disc blackbody + blackbody model from Lavagetto et al. (2008), and freeze our blackbody temperature to the 1.54 keV value they find, and freeze our disc blackbody temperature to the 0.815 keV value they find. Since they use *XMM–Newton* data with a broader bandpass than our *Chandra* data cover, there is no risk that the extrapolation of their spectrum to our energy range will result in an unacceptable fit because of a poor model. We find that, when varying only the normalizations of the model component and the foreground $N_{\rm H}$, an acceptable fit is obtained, with $\chi^2/\nu = 17.2/14$, and a null hypothesis probability of 0.25. While a low magnetic field for a neutron star in such a young population is unlikely, the Galactic source Circinus X-1, for example, seems to be such an object (Boutloukos et al. 2006), so the possibility remains viable (e.g. the LMC, which is the galaxy for which we took our prototype source LMC X-2, is also a star-forming galaxy).

4 INTERPRETATION AS A WOLF–RAYET X-RAY BINARY

While a periodicity cannot be clearly established given the lack of intensive sampling of the source’s variability, we still argue that the most likely explanation for the observed variability is that it is the orbital modulation of the X-ray flux due to the changes in the absorption from the stellar wind of a Wolf–Rayet X-ray binary.

The location of the source in a star-forming galaxy suggests that the source is likely to be some kind of high-mass X-ray binary, particularly since the presence of a supernova remnant within 2 arcsec (projected distance of 25 pc) of the source (Collison et al. 1994) indicates that it is in a region of current active star formation. We thus focus on high-mass X-ray binary interpretations for the source, but also consider low-mass X-ray binary possibilities later. We cannot make any definitive statements about the nature of the source’s optical counterpart because there are not any optical or infrared data which are deep enough and have astrometry sufficiently well-tied to the X-ray data.

If the variations are periodic, then they almost certainly represent the orbital period of a Wolf–Rayet X-ray binary. Large amplitude periodicities are generally not found in accreting black hole systems, except on the orbital time-scale. Quasi-periodicities have been suggested in several systems to take place on time-scales of a few tens of orbital periods (e.g. Smale & Lochner 1992), with the most common explanation being modulation due to precession of a warped accretion disc (e.g. Maloney & Begelman 1997; Wijers & Pringle 1999). Some neutron star systems show strong periodic modulations as X-ray pulsars; a pulse period of 14–15 h coupled with a peak luminosity of 10^{38} erg s^{-1} would require a magnetic field several orders of magnitude larger than any seen to date (e.g. Ghosh & Lamb 1978), and can be taken as unlikely.

If the periodicity is real and orbital, and the system is a high-mass X-ray binary, then the donor star must be a Wolf–Rayet star. The density of the donor star of a Roche lobe overflowing system is solely a function of its orbital period:

$$\rho = 107 P_{\rm orb,h}^{-2}\,{\rm g\,cm^{-3}}, \qquad (1)$$

from combining the Paczyński (1971) formula for the Roche lobe size with Kepler’s third law (see e.g. Knigge, Baraffe & Patterson 2011).

The mass–radius relation of main-sequence stars above 1.66 M$_\odot$ is given by:

$$\log R = 0.12 + 0.55 \log M, \qquad (2)$$

with R and M in solar units (Demircan & Kahraman 1991). We can then see that the density of a 8 M$_\odot$ star will be about 0.1 g cm^{-3}, while the Roche lobe density of a star in a 14.5 h orbit will be 0.5 g cm^{-3}, so the 8 M$_{\odot}$ star will overfill its Roche lobe rather dramatically; for the period to be orbital, the system must either have a relatively dense, and hence low-mass donor star, or it must have a donor star which has lost its envelope (i.e. a Wolf–Rayet star). While some low-mass X-ray binaries do show modulation on their orbital periods, these tend to be quite low amplitude unless the systems are eclipsing, and the eclipsers tend to show sharp ingresses and egresses due to the small X-ray emission regions (e.g. Wolff et al. 2009).

Next, we can consider possibilities for aperiodic variability from the system. In this case, the key parameters remain the relatively long time-scale of variations and the large amplitude of variations. We can consider the variations in persistent systems with similar peak X-ray luminosities. These are largely the Z-sources. Looking at the RXTE All-Sky Monitor light curves for the two best-studied Z-sources, Sco X-1, and Cyg X-2, we see that neither varies at all by more than a factor of about 3. Consulting the High Energy Astrophysics Virtually Enlightened Sky (HEAVENS) data base of *INTEGRAL* data (Walter et al. 2010), we see also that the accreting pulsar Vela X-1 similarly rarely varies by more than a factor of a few when out of eclipse – and is, in any event, at a much lower luminosity than this object – in fact, all Galactic accreting pulsars are (see Lutovinov et al. 2013 for a compilation). It is also difficult to envision from empirical data how a black hole system would show such strong variations on these time-scales – while the accreting black hole system GRS 1915+105 shows similarly strong variability on time-scales of hours (e.g. Belloni et al. 2000; Rodriguez et al. 2008), it does so at luminosities near the Eddington limit, and the variations may be due, in part, to e.g. thermal instabilities for systems highly affected by radiation pressure (e.g. Szuszckiewicz & Miller 1998).

Evidence for quasi-periodic oscillations in the Galactic high magnetic field neutron star X-ray binary EXO 2030+375 has also been seen (Klochkov et al. 2011). The authors argue that the mechanism is the formation of a 'reservoir' of gas when the magnetosphere of the neutron star truncates the accretion disc on to the neutron star outside of, but close to, the neutron star co-rotation radius (D'Angelo & Spruit 2010). The reservoir is then drained on a viscous time-scale once enough material has piled up to overwhelm the neutron star's magnetic field. This mechanism is unlikely to explain a $\sim$15 h periodicity for this source – the quasi-periodicity seen in ESO 2030+375 is about 7 h, and scales linearly with the spin period of the neutron star. Given that this source appears to be persistently very bright it is likely to be a Roche Lobe overflowing HMXB, if it is a neutron star HMXB accretor at all, and then correlations between orbital period and spin period for Roche lobe overflowers would yield an expected spin period several times shorter than the spin period of 40 s seen in EXO 2030+375 (Corbet 1986).

When comparing the behaviour of CXOU J004732.0−251722 with the phenomenological behaviour of Galactic X-ray sources, it appears most likely that the variability seen is periodic and orbital; the chief caveat would be the possibility that the source is behaving in an unusual manner relative to the observed phenomenology of Galactic sources, despite being in a luminosity range which is fairly common for Galactic sources.

We can also argue that the source is more likely to have a black hole accretor than a neutron star accretor on the basis of its X-ray luminosity – Linden et al. (2012) performed a population study of neutron star X-ray binaries with naked helium star donors and found that for orbital periods of $\sim$1 d the X-ray luminosities were typically less than 10^{37} erg s^{-1}. While it may be possible either that the mass-loss rates are higher than predicted by the Hurley, Pols & Tout (2000) formalism used by Linden et al. (2012), or that the accretion is more efficient than Bondi & Hoyle (1944), the luminosity being so high is at least a point in favour of the idea that the accretor is a black hole, and that the donor is a relatively massive Wolf–Rayet star. We thus conclude that, while we cannot firmly establish either a periodicity in this source or the mass of the compact object, the most likely explanation for all its properties is that it is a black hole X-ray binary with a Wolf–Rayet companion. Additional data sets which could help verify the nature of the source would be a better sampled X-ray light curve, which could establish or refute the periodicity, and a deep infrared spectroscopy campaign, which could find moving emission lines from the donor star.

5 CONVERTING THE OBSERVED WOLF–RAYET BINARIES INTO A MERGER RATE

Theoretical uncertainties of a factor of about 1000 exist in predictions of the rate of which ground-based gravitational wave detectors will discover sources (Abadie et al. 2010), motivating a more empirical basis for making predictions. Procedures have been developed in the past for converting small numbers of observed systems into empirical event rates in the case of using the observed double neutron star systems to estimate event rates for double neutron star mergers (see Kim, Kalogera & Lorimer 2003 for a recent example; Clark, van den Heuvel & Sutantyo 1979 for the first example). For understanding neutron star mergers on the basis of double neutron stars, one of the chief uncertainties comes from understanding the selection effects in pulsar surveys (see e.g. Narayan 1987).

For understanding the rate of double compact object mergers on the basis of populations of high-mass X-ray binaries, considerably greater uncertainties are present. In general, because the second supernova has not yet taken place, one needs to make assumptions about the velocity kick distributions of the second supernova explosions. Additionally, the mass and radius of the donor star are often difficult to measure, especially in the cases of Wolf–Rayet stars, where it is difficult to see down to the stellar photosphere through the stellar wind.

For understanding the mergers of two neutron stars, the double neutron stars themselves are obviously a superior sample of objects with which to work. For understanding mergers involving black holes, on the other hand, the double neutron stars are obviously of no use, so either one is stuck with using purely theoretical calculations (e.g. Belczynski et al. 2007) or one must attempt to forge ahead with observations of X-ray binaries, aware of the extra complications in interpreting their populations, and the greater uncertainties involved. Eventually, of course, some pulsar/black hole binaries may start to be discovered, which could allow for the same kind of empirical approach used for double neutron stars to be applied to neutron star–black hole binaries. A hybrid approach can be used, as well, which identifies families of models that are consistent with the existing observations of X-ray binaries; some success has been obtained in recent years in modelling the X-ray luminosities and luminosity functions of late-type galaxies, suggesting that this approach has great potential (e.g. Tremmel et al. 2013; Tzanavaris et al. 2013).

A procedure can be outlined for how to deal with this conversion for high-mass X-ray binaries as follows.

(i) Identify the binary, and estimate its parameters.

(ii) Follow the evolution of the binary using a binary evolution code until it becomes a double black hole or a black hole/neutron star binary. Estimate its lifetime as an X-ray binary, t_X.

(iii) Compute the merger time-scale, t_{merge}. If the merger time-scale is larger than a Hubble time, then the object can be ignored. Otherwise continue.

(iv) Compute the radius out to which the object could be detected as a gravitational wave source, r_{detect}.

(v) Compute the star formation rate per comoving volume, $\dot{\rho}_{tform}$, of the Universe at lookback time t_{merge}, using one of the compilations of cosmic star formation history (e.g. Lilly et al. 1996; Madau et al. 1996; Hopkins 2004), and divide by the local star formation rate (e.g. from the 11 HUGS[1] compilation of Lee et al. 2009 which includes all star-forming galaxies out to 11 Mpc distance), to get the amplification factor A due to the fact that the gravitational wave events seen now are produced at times when the cosmic star formation rate was quite different from that now.

(vi) Integrate out the total star formation rate, $\dot{\rho}_{detect}$ within r_{detect}. For double black hole mergers with LIGO, r_{detect} will generally be large enough that one need not worry about the effects of being located within regions of large-scale structure that are not representative of the mean properties of the Universe, and small enough that one need not worry about the lookback time to the outer part of the volume; with Advanced LIGO, a somewhat more sophisticated calculation will be necessary to deal with the lookback time issue.

(vii) Calculate the total star formation rate of galaxies which have been searched effectively for high-mass binaries with similar X-ray luminosity and orbital period to the source under consideration, $\dot{\rho}_{search}$. Note that at the present time, the strong candidates all have $L_X = 10^{38}$ erg s^{-1} and all have orbital periods less than about 1.5 d, so they probably all could have been detected in all the galaxies searched.

Each detected high-mass binary will then contribute an expectation value of $(\frac{A}{t_X})(\frac{\dot{\rho}_{detect}}{\dot{\rho}_{search}})$ per year of gravitational wave events. A lower limit on the gravitational wave source detection rate can then be estimated by summing over the detected objects. This analysis ignores some possible additional factors – e.g. the metallicity at which star formation typically takes place at moderate to high redshift may differ from the metallicity at which star formation takes place at the present time. Lower metallicity stars may leave behind higher mass black holes (e.g. Belczynski et al. 2010). Additionally, such an analysis ignores binaries formed through other mechanisms, such as those formed dynamically in globular clusters (e.g. Portegies Zwart & McMillan 2000) – a possibility that seems even more likely now than it did when first proposed, given the discoveries of black hole X-ray binaries in both extragalactic (Maccarone et al. 2007) and Galactic (Strader et al. 2012) globular clusters.

For simplicity, in this paper, we make an illustrative calculation in which we will assume that the donor high-mass stars collapse promptly into black holes of 10 $M_\odot$ at the current orbital period, and that the black holes already present in these systems are of about 10 $M_\odot$. This is below the estimates made for the black holes in IC 10 X-1 (Prestwich et al. 2007; Silverman & Filippenko 2008) and NGC 300 X-1 (Crowther et al. 2010), an issue we discuss in Section 5.1. This assumption is obviously extremely crude, as it neglects the effects of orbital period evolution, possible second common envelope phases of stellar evolution, and supernova kicks.

[1] This acronym stands for the 11 Mpc Hα UV Galaxy Survey.

A proper treatment of the problem would require running binary evolution calculations starting from the present conditions – which themselves are presently poorly understood. We emphasize that estimates done without undertaking proper binary evolution calculations should not be taken too seriously, and that the purpose of the calculation here is simply to illustrate that single object detections can have significant implications for theoretical estimates of gravitational wave detection rates.

Let us consider, then, a system that begins in an orbital period of 14 h, and has two black holes, each of 10 $M_\odot$. The semi-major axis of the binary is then 5.6×10^{11} cm. Pfahl, Podsiadlowski & Rappaport (2005) provide a useful expression for t_{merge}, based on the work of Peters (1964). for circular binaries, this is:

$$t_{merge} = 2.1\,\mathrm{Myr}\left(\frac{P_b}{\mathrm{hr}}\right)^{\frac{8}{3}}\left(\frac{m_1+m_2}{10\,M_\odot}\right)^{\frac{-2}{3}}\left(\frac{\mu}{M_\odot}\right)^{-1} \quad (3)$$

where m_1 and m_2 are the masses of the binary components, and μ is their reduced mass, P_b is the binary's orbital period, and e is its eccentricity. For eccentric binaries, one must multiply through by an additional factor of $(1-e^2)^{\frac{7}{2}}$. Then, if we consider a circular initial binary, we get t_{merge} of about 300 Myr. Given this lookback time, the local star formation rate for the Universe can be used, so $A = 1$. The radius out to which LIGO should be able to detect mergers of two 10 $M_\odot$ black holes is about 90 Mpc, so we can take about 8^3 times the star formation rate of the 11 HUGS survey as the estimate of the total enclosed star formation rate – so we can presume that LIGO is sensitive to about 6000 $M_\odot$ yr^{-1} worth of star formation. At the present time, there are no indications that careful searches which would exclude a Wolf–Rayet nature have been done for any galaxies other than those for which detections have been reported. We can thus take the 11 HUGS star formation rates for the moderately distant galaxies for which detections have been made, NGC 253, NGC 300, IC 10, and the Milky Way, obtaining roughly 4 $M_\odot$ yr^{-1}, with considerable uncertainty in the star formation rate of the Milky Way. We find, then that based on our new NGC 253 system alone, the birth rate of gravitational wave sources is only about 2×10^{-3} per year, assuming $t_X \approx 10^6$ yr. However, enclosing a volume a factor of about 4000 larger, as Advanced LIGO should do, would bring the event rate up to ∼10 per year, based on this object alone. Furthermore, we note that systems with orbital periods of a factor of 2.5 longer would have t_{merge} about 11 times as long, meaning that they would have to be formed about 3–4 Gyr before the black holes merge, bringing them back to $z \sim 0.3$ if they merger locally, or $z \sim 1$ for sources detected near the edge of Advanced LIGO's distance range. This would then allow an additional enhancement in the event rate due to the significantly higher star formation rate at $z \sim 1$ than today. This point may apply to IC 10 X-1 and NGC 300 X-1.

5.1 The van Kerkwijk model of photoionized winds in Cyg X-3 and the masses of black holes in Wolf–Rayet binaries

In recent years, attempts have been made to measure radial velocity curves for extragalactic high-mass X-ray binaries by following their emission lines around the system orbit (Prestwich et al. 2007; Silverman & Filippenko 2008; Crowther et al. 2010). While the measurements may be correct, emission line tracers of orbital motions in X-ray binaries are often unreliable. In Cygnus X-3, it has been shown that the radial velocities estimated from infrared emission lines have their maximum blueshift at the X-ray and infrared photometric minimum, and show their maximum redshift half an orbit further along in phase (van Kerkwijk 1993). A natural interpretation of the relative phasing of the photometric and spectroscopic time series is that the X-ray source photo-ionizes the entire stellar wind, except for the component which is shielded by the donor star itself. As a result, the radial velocity curve of the wind line does not trace out the centre-of-mass velocity of the star, but a particular convolution of the centre-of-mass velocity and the wind speed itself. Under the assumption that the wind speed is larger than the orbital velocity (which, in fact, follows from the system being detached), then the amplitude of velocity variations is, essentially, just giving a value close to the wind speed, and hence is a reliable probe of neither the radial velocity of the donor star nor the mass of the compact object.

That the same phenomenon would take place for the cases of IC 10 X-1 (Prestwich et al. 2007; Silverman & Filippenko 2008) and NGC 300 X-1 (Crowther et al. 2010) does not follow immediately from its taking place for Cygnus X-3. The X-ray luminosities of all three systems are about the same, but the orbital period of Cygnus X-3 is a factor of about 7 shorter, meaning that the system separations are likely to be smaller as well, and the ionization parameter of the wind may be smaller for the extragalactic systems than for Cyg X-3. Nonetheless, there are hints in both cases that this phenomenon is, in fact, relevant to the two extragalactic systems. In particular, in both systems, the emission lines have a larger full-width half-maximum for the phases where they have nearly zero central velocity than for the phases near maximum blue shift or redshift (see table 1 of Silverman & Filippenko 2008, and fig. 1 of Crowther et al. 2010). A more definitive determination of whether the lines trace out the stellar wind velocity or the orbital velocity or some combination of the two could be obtained by taking several spectra close enough in time to a long X-ray observation that one could test the relative phasing of the two time series.

6 SUMMARY

We have presented evidence that the X-ray source CXOU J004732.0−251722.1 in the galaxy NGC 253 is likely to be a Wolf–Rayet X-ray binary – the fourth member of the class discovered to date. The evidence consists of the discovery of large amplitude X-ray variability from the source which is consistent with being periodic on a time-scale of about 14–15 h, and the source's location in the centre of a nuclear starburst galaxy. We have also discussed how the detections of individual Wolf–Rayet X-ray binaries may have implications for the expected rate of gravitational wave source detections, and have illustrated both a path to using these sources for such a purpose and several of the key challenges that will be faced in applying that methodology.

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