

# Monitoring of the eclipsing Wolf-Rayet ULX in the Circinus galaxy

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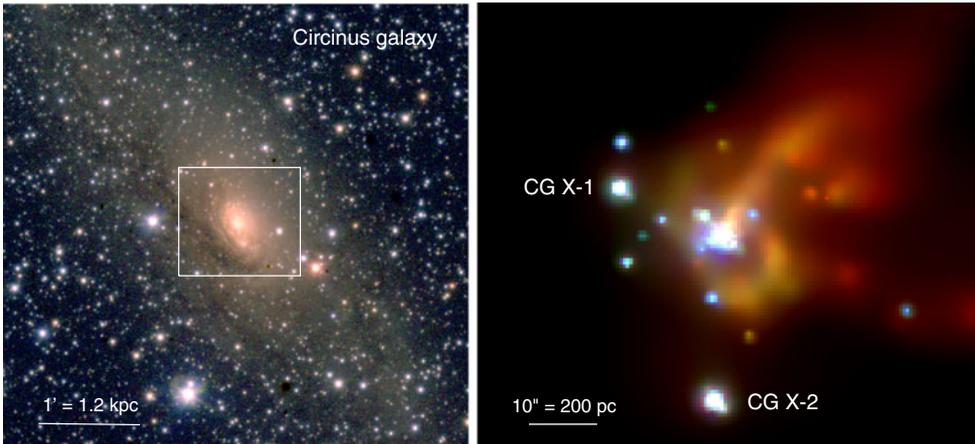
**Abstract.** We studied the eclipsing ultraluminous X-ray source CG X-1 in the Circinus galaxy, re-examining two decades of *Chandra* and *XMM-Newton* observations. The short binary period (7.21 hr) and high luminosity ( $L_X \approx 10^{40}$  erg s<sup>-1</sup>) suggest a Wolf-Rayet donor, close to filling its Roche lobe; this is the most luminous Wolf-Rayet X-ray binary known to-date, and a potential progenitor of a gravitational-wave merger. We phase-connect all observations, and show an intriguing dipping pattern in the X-ray lightcurve, variable from orbit to orbit. We interpret the dips as partial occultation of the X-ray emitting region by fast-moving clumps of Compton-thick gas. We suggest that the occulting clouds are fragments of the dense shell swept-up by a bow shock ahead of the compact object, as it orbits in the wind of the more massive donor.

**Keywords.** X-rays: binaries, X-rays: individual (Circinus Galaxy X-1), stars: Wolf-Rayet, binaries: eclipsing

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## 1. Introduction

The Circinus galaxy, located at a distance of 4.2 Mpc (Tully *et al.* 2009), contains a bright, point-like X-ray source known as CG X-1, seen at a projected distance of  $\approx 300$  pc from its starburst nucleus (Figure 1). The interpretation of this source has been the subject of debate for the past two decades (Bauer *et al.* 2001; Weisskopf *et al.* 2004; Esposito *et al.* 2015). There are at least three features that make this object interesting and unusual. The first one is its high luminosity. If it is indeed located inside the Circinus galaxy (rather than being a foreground or background object), its average X-ray luminosity would be  $\approx 10^{40}$  erg s<sup>-1</sup>; this would place CG X-1 near the top of the luminosity distribution of ultraluminous X-ray sources (ULXs) in the local universe: a factor of 10 times above the Eddington luminosity of Galactic stellar-mass black holes (BHs), or 100 times above the Eddington limit of a neutron star (NS). When CG X-1 was first discovered (Bauer *et al.* 2001), observational and theoretical understanding of super-Eddington X-ray binaries was still in its infancy; however, today we know such sources exist and we can quantify their population properties. Based on the star formation rate of Circinus ( $\approx 3\text{--}8 M_\odot \text{ yr}^{-1}$ ; For *et al.* 2012) and on the X-ray luminosity function of Mineo *et al.* (2012), we expect  $\approx 0.2\text{--}0.6$  X-ray binaries with a luminosity of  $10^{40}$  erg s<sup>-1</sup> or above, in that galaxy. Alternative interpretations, for example that of a foreground CV (Weisskopf *et al.* 2004), can be rejected based on its high X-ray/optical flux ratio (Bauer *et al.* 2001; Qiu *et al.* in preparation), as well as the low probability of finding a foreground Galactic source projected onto the starforming nucleus of Circinus.



**Figure 1.** Left panel: true-colour optical image of the Circinus galaxy in the  $g,r,i$  filters; data from the 2.6-m ESO-VLT Survey Telescope. North is up and east to the left. The white box is the area displayed in the *Chandra* image. Right panel: adaptively smoothed *Chandra*/ACIS image of the innermost region of the galaxy; red = 0.3–1.1 keV, green = 1.1–2.0 keV, blue = 2.0–7.0 keV. The two brightest non-nuclear X-ray sources are known as CG X-1 (the ULX subject of our investigation) and CG X-2 (also known as SN 1996cr: [Bauer et al. 2008](#)). A powerful outflow of hot thermal plasma from the nuclear starburst is well visible to the west of the nucleus, but the soft diffuse emission is absorbed by thick dust to the east of the nucleus.

The second interesting property of CG X-1 is the periodicity identified in its X-ray lightcurve. Most ULXs show stochastic variability by a factor of a few; in a few cases, periodic signals of a few days (*e.g.*,  $\approx 2.5$  d in M 82 X-2: [Bachetti et al. 2014](#); either  $\approx 6$  d or  $\approx 13$  d in M 51 ULX-1: [Urquhart & Soria 2016a](#);  $\approx 8.2$  d in M 101 ULX-1: [Liu et al. 2013](#)) or even weeks ( $\approx 63$  d for NGC 7793 P13: [Motch et al. 2014](#)) have been identified and interpreted as the binary periods. CG X-1 stands out with an unambiguous X-ray period of only 7.2 hr, determined from its eclipsing behaviour ([Esposito et al. 2015](#)). This period is too short to be consistent with a supergiant donor; it suggests instead a Wolf-Rayet donor, whose radius is small enough to fit into such a compact binary system. In any case, CG X-1 is the ULX with the most precisely known binary period.

The third intriguing feature of CG X-1 is the nature of its X-ray eclipses. Although the period is stable (X-ray lightcurves observed twenty years ago can still easily be phase connected with recent observations) and the phase-averaged lightcurve is superficially consistent with the eclipse of the compact object behind the donor star, our study of the individual cycles tells a different story. Each cycle has a different pattern of eclipse duration and dipping morphology.

In this work, we will focus on the second and third property outlined above (short period and eclipse behaviour). We will discuss the general properties of the source in and out of eclipse, and the physical origin of the eclipses. We will then briefly discuss the possible origin and future evolution of this system, and how its existence compares with the detection rate of gravitational wave events.

## 2. The most luminous Wolf-Rayet ULX

There is an unresolved optical counterpart detected in the only (short) *Hubble Space Telescope* observation of the field, within the *Chandra* error circle for CG X-1. We estimate an apparent brightness  $m_{F606W} \approx V \approx 24.3 \pm 0.1$  mag in the Vega system; the distance modulus of Circinus is  $\approx 28.1$  mag. Unfortunately, the optical extinction is very high, because Circinus is located behind the disk of the Milky Way; the line-of-sight extinction

**Table 1.** Summary of candidate Wolf-Rayet X-ray binaries, in order of increasing period.

Name	Galaxy	Distance (Mpc)	Peak $L_{0.3-10}^a$ (erg s <sup>-1</sup> )	Period hr	References
CXOU J121538.2+361921	NGC 4214	3.0	$\approx 6 \times 10^{38}$	3.6	1
Cygnus X-3	Milky Way	0.0074	$\approx$ a few $\times 10^{38}$	3.6	2,3,4,5
CXOU J123030.3+413853	NGC 4490	7.0	$\approx 1 \times 10^{39}$	4.8	6
<b>CG X-1</b>	<b>Circinus</b>	<b>4.2</b>	<b><math>\approx 3 \times 10^{40}</math></b>	<b>7.2</b>	<b>7,8</b>
CXOU J004732.0–251722	NGC 253	3.2	$\approx 1 \times 10^{38}$	14.5	9
CXOU J005510.0–374212 (X-1)	NGC 300	1.9	$\approx 3 \times 10^{38}$	32.8	10,11,12,13
CXOU J002029.1+591651 (X-1)	IC 10	0.7	$\approx 7 \times 10^{37}$	34.8	14,11,15,16
<sup>b</sup> CXOU J140332.3+542103 (ULX-1)	M 101	6.4	$\approx 4 \times 10^{39}$	196.8	17,18,19

*References:*

1: Ghosh *et al.* (2006); 2: Hjalmarsdotter *et al.* (2009); 3: Koljonen *et al.* (2010); 4: Zdziarski *et al.* (2012); 5: McCollough *et al.* (2016); 6: Esposito *et al.* (2013); 7: Esposito *et al.* (2015); 8: Qiu *et al.*, in prep.; 9: Maccarone *et al.* (2014); 10: Carpano *et al.* (2007); 11: Barnard *et al.* (2008); 12: Crowther *et al.* (2010); 13: Binder *et al.* (2011); 14: Prestwich *et al.* (2007) 15: Silverman & Filippenko (2008) 16: Laycock *et al.* (2015) 17: Kong *et al.* (2004); 18: Liu *et al.* (2013); 19: Urquhart & Soria (2016b).

*Notes:*

<sup>a</sup>De-absorbed 0.3–10 keV luminosity in the bright phase of the orbital cycle; values taken from the references listed in this Table, but rescaled to the distance adopted here.

<sup>b</sup>M 101 ULX-1 differs from the other seven sources because it is an ultraluminous supersoft source, it does not show eclipses, and its binary separation is too large to permit a BH-BH merger in a Hubble time.

towards the Circinus galaxy is  $A_V \approx 4$  mag (Schlafly & Finkbeiner 2011), but additional local extinction is highly likely (see also Weisskopf *et al.* 2004) and uncertain, given the location of the source near dust lines. This, coupled with the lack of observations in any other optical/IR band, make it impossible to determine the nature of this object (let alone its time variability). Thus, the main constraints to the nature of the system must come from the X-ray data.

From our study of all the archival *ROSAT*, *Chandra* and *XMM-Newton* observations between 1997 March and 2018 February (see Qiu *et al.*, in prep., for a detailed log), we derived an average binary period  $P = 25,970.1 \pm 0.1$  s  $\approx 7.214$  hr. Using the period-density relation for binary systems (Eggleton 1983), we obtain an average density of  $\rho \approx 1.2\rho_\odot \approx 1.7$  g cm<sup>-3</sup> inside the Roche lobe of the donor star, for a mass ratio  $M_2/M_1 = 2$  (where  $M_2$  is the mass of the donor star), or  $\rho \approx 0.74\rho_\odot \approx 1.1$  g cm<sup>-3</sup>, for  $M_2/M_1 = 10$ . This range of values already rules out main-sequence OB stars (in fact, any main-sequence star more massive than  $\approx 1 M_\odot$ ), blue supergiants, red supergiants or red giants. The persistent nature of the X-ray source over at least 20 years, and its location in a highly star-forming region, strongly suggest a young system with a donor star more massive than the compact object. A Wolf-Rayet star is consistent with all those constraints. If CG X-1 contains a  $20-M_\odot$  Wolf-Rayet star and a  $10-M_\odot$  BH, the binary separation is  $\approx 5.8 R_\odot$  and the size of the Roche Lobe of the star is  $\approx 2.6 R_\odot$ : this is large enough to contain a Wolf-Rayet but not any other type of massive star. Cygnus X-3 is the prototypical example of a high-luminosity X-ray binary with a very short binary period, fed by a Wolf-Rayet star. Very few such systems are known to-date (Table 1).

From our spectral modelling, we found (Qiu *et al.*, in prep.) that the de-absorbed X-ray luminosity of CG X-1 is  $\approx 10^{40}$  erg s<sup>-1</sup> during the out-of-eclipse parts of the orbital cycle, with a variability range of a factor of four above and below this value, over two decades<sup>†</sup>. Such extreme luminosity implies a mass accretion rate onto the compact object of at least  $\approx 10^{-6} M_\odot$  yr<sup>-1</sup>, for a radiative efficiency  $\eta \approx 0.15$ . In fact, the radiative efficiency is likely to be lower, scaling as  $\eta \sim 0.1(1 + \ln \dot{m})/\dot{m}$  for super-Eddington accretion, where  $\dot{m}$  is the accretion rate in Eddington units (Shakura & Sunyaev 1973; Poutanen *et al.*

<sup>†</sup> The highest out-of-eclipse luminosity ( $L_X \approx 3.8 \times 10^{40}$  erg s<sup>-1</sup>) was measured from the *XMM-Newton* observation of 2001 August 6, and the lowest value ( $L_X \approx 2.3 \times 10^{39}$  erg s<sup>-1</sup>) was recorded in the *Chandra* observation of 2008 October 26.

2007). Moreover, the eclipsing and dipping behaviour suggests a high viewing angle, so that we cannot invoke geometric beaming of the emission via a polar funnel. Thus, it appears that the system is really accreting at least several times  $10^{-6} M_{\odot} \text{ yr}^{-1}$ . Such high accretion rate suggests that the donor star is either filling the Roche lobe, or at least that its wind is gravitationally focused towards the compact object. Note that CG X-1 is the only system among candidate Wolf-Rayet X-ray binaries with a luminosity  $\sim 10^{40} \text{ erg s}^{-1}$ ; all others have X-ray luminosities  $\lesssim 10^{39} \text{ erg s}^{-1}$ , consistent with wind accretion.

### 3. Periodic eclipses and stochastic dipping

Folded X-ray lightcurves (Fig. 6 in [Esposito \*et al.\* 2015](#); [Qiu \*et al.\*](#), in prep.) show a sharp flux drop in ingress, followed by an eclipse phase lasting for  $\approx 1/5$  of the period, with faint residual emission (softer than out-of-eclipse), and then a slow return to the baseline flux. This structure is reminiscent of other high-mass X-ray binaries seen at high inclination, with a proper eclipse (apart from residual scattered photons) when the accreting object is behind the donor star, and varying absorbing column density at other phases, as the compact object moves through the wind of the donor. However, an inspection of the individual lightcurves of CG X-1 from each observed cycle tells a more complicated story (Figure 2). Any model of the system must explain the following two X-ray properties:

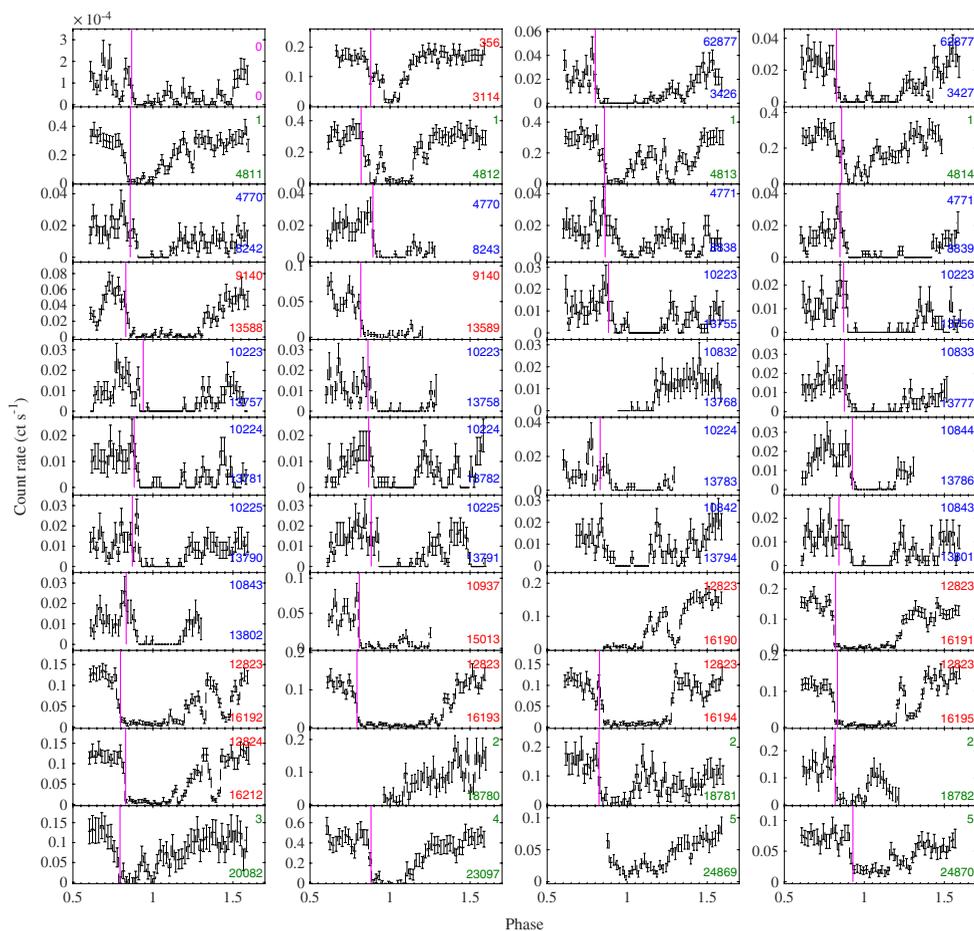
*a) the eclipse and dipping patterns and duration of the egress phase change from orbit to orbit.* Clearly, the size of the donor star and the binary separation cannot change; therefore, the eclipse and the dips must be (at least partly) caused by optically thick material (*e.g.*, clouds) in front of the X-ray source, moving on timescales shorter than the binary period.

*b) the transition from full eclipse to full flux level consists of a decreasing level of partial covering by an optically thick medium.* A sequence of X-ray spectra show ([Qiu \*et al.\*](#), in prep.) that during the egress phase, the intrinsic spectral shape and cold absorption remain the same, and the difference is only the value of a normalization constant. In other words, the flux recovery is not caused by a gradual decrease of absorbing column density. Instead, we propose that Compton-thick clouds ( $N_{\text{H}} > 1.5 \times 10^{24} \text{ cm}^{-2}$ ) occult a variable fraction (between 0 and 100%) of the emitting region during each orbital cycle.

The occulting clouds cannot be uniformly or randomly distributed along all azimuthal angles, because the observed pattern of fast ingress, total eclipse, and dips during the slow egress is regularly repeated for two decades. In some low-mass X-ray binaries seen at high inclination, regular dipping behaviour is also observed, probably caused by the thick bulge where the accretion streams impacts the disk ([White & Swank 1982](#); [Frank \*et al.\* 1987](#) 1987). However, this scenario does not work for CG X-1, because the accretion stream always trails the compact object, and would produce most dips just before or during eclipse ingress, contrary to the observed pattern. High-mass X-ray binaries sometimes also have an asymmetric eclipse profile due to a thick accretion stream (for example, Vela X-1: [Doroshenko \*et al.\* 2013](#)), and in those cases, too, a slow ingress is followed by a fast egress (opposite to CG X-1).

Taking those constraints into account, we suggest that the optically thick material is located between the Wolf-Rayet and the compact object, but mostly in front of the compact object. This configuration will lead to partial occultations of the X-ray emission after the compact object has passed behind the star and is moving towards us (egress), rather than before.

We know that the ULX must have a strong, radiatively driven wind (*e.g.*, [Poutanen \*et al.\* 2007](#), [Ohsuga & Mineshige 2011](#)), probably comparable in speed and mass density to that of the Wolf-Rayet. We also estimate an orbital velocity  $\approx 700 \text{ km s}^{-1}$  for a typical  $10 M_{\odot}$  stellar-mass BH orbiting a typical Wolf-Rayet star ( $M_2 \approx 20\text{--}30 M_{\odot}$ ). This implies



**Figure 2.** Twenty years of X-ray lightcurves for CG X-1, showing that each orbital cycle is different than the others, although some general underlying features remain the same. All lightcurves (apart from the one from *ROSAT*/HRI) are in the 0.3–8 keV band, and are binned to 500 s per bin. All lightcurves are folded on our best-fitting ephemeris; phase  $\phi = 1$  occurs at  $\text{MJD} = 50681.327156 + 0.300580(\text{d}) \times N$ . See Qiu *et al.*, in prep., for details of how the ingress time and the ephemeris were calculated. In each panel, the number at the bottom right corresponds to the value of  $N$  for the orbital cycle represented in that panel. The vertical magenta bar in each panel shows the estimated centre time of the eclipse ingress phase for that observation. The top left panel (labelled 0) is a *ROSAT*-HRI lightcurve from 1997; the numbers on the top right of all the other panels are short forms of the corresponding observation IDs from which those lightcurves were extracted. Red numbers (*e.g.*, 356): ObsID of a *Chandra*/ACIS-S3 observation; blue numbers (*e.g.*, 62877): ObsID of a *Chandra*/HETG observation; green numbers (*e.g.*, 1): ObsID of an *XMM-Newton*/EPIC observation, where 1, 2, 3, 4, 5 mean 0111240101, 0701981001, 0656580601, 0792382701, 0780950201, respectively. *XMM-Newton*/EPIC lightcurves are extracted from MOS1 + MOS2 for observations 1, 2, 3 and 5, and from EPIC-pn for observation 4.

that the compact object is ploughing through the thick wind of the donor star at highly supersonic speed (Mach number  $\mathcal{M} \approx 20$  for a wind temperature  $\approx 10^5$  K).

In general, in systems with a Wolf-Rayet star and an O star, a denser, optically-thick layer of shocked gas forms at the interface of the two winds; in CG X-1 we have the additional element that the compact object is moving at supersonic speed. We suggest that the compact object creates a bow shock along its direction of motion, and sweeps up a dense shell of shocked Wolf-Rayet wind; for a radiative shock, the density enhancement

scales as  $\mathcal{M}^2$ , from standard bubble theory (*e.g.*, Weaver *et al.* 1977). Thus, for typical ambient densities  $n_e \sim 10^{14} \text{ cm}^{-3}$  (Ro & Matzner 2016) in the undisturbed wind, the density in the shocked shell can exceed  $10^{16} \text{ cm}^{-3}$  and lead to rapid cooling. By analogy with Wolf-Rayet/O-star binaries (Usov 1991), a cold dust layer may form at the contact discontinuity between the shocked Wolf-Rayet wind and the shocked accretion-disk wind. For an order-of-magnitude estimate, we can assume a radius of the shell comparable to the Roche Lobe of the accreting object ( $R \sim 10^{11} \text{ cm}$ ) and a thickness of the shell  $\sim 10^9 \text{ cm}$ : thus, the equivalent hydrogen column density in the swept-up shell can exceed  $10^{25} \text{ cm}^{-2}$  and cause total occultation of the X-ray emission below 10 keV.

For high Mach numbers, hydrodynamic instabilities of the swept-up, cooling shell lead to continuous fragmentation and re-formation (Park & Ricotti 2013). We argue that fragments of the swept-up shell are the optically thick structures responsible for the irregular dipping in CG X-1. If this is the case, we expect to see occultations and dips in the X-ray lightcurve mostly when the compact object moves towards us (after egress from the eclipse), rather than before ingress.

#### 4. Conclusions

We have summarized some of the most interesting properties of the ULX CG X-1 in the Circinus galaxy. Its short orbital period (7.2 hr) makes it a strong candidate Wolf-Rayet X-ray binaries, a very rare system (less than 10 known to-date) with intriguing accretion physics. If the compact object is a stellar-mass BH and the Wolf-Rayet collapses into another BH (without disrupting the binary), the timescale for a gravitational merger is only  $\approx 50 \text{ Myr}$  (Esposito *et al.* 2015). In addition, CG X-1 is one of the most luminous ULXs in the nearby universe, reaching peak luminosities in excess of  $3 \times 10^{40} \text{ erg s}^{-1}$  at some epochs. By contrast, all other Wolf-Rayet X-ray binaries have luminosities  $\lesssim 10^{39} \text{ erg s}^{-1}$ . Thirdly, the X-ray lightcurve shows a regular pattern of eclipses with fast ingress and slow egress (with a coherent phase over 20 years of observation), modified by an irregular pattern of deep dips, changing every orbital cycle. We have discussed a possible origin for the dips. We suggested that the CG X-1 differs from sub-Eddington Wolf-Rayet systems such as Cyg X-3 because both the primary and the secondary launch a massive radiatively driven outflow. In fact, the gas environment in systems such as CG X-1 may be compared to binary Wolf-Rayet systems.

In short, CG X-1 is an exceptional test case for studies of the progenitors of gravitational wave events and their expected rate in the local universe; for studies of accretion and outflows in ULXs; and for studies of the hydrodynamics of colliding winds and shock-ionized bubbles.

In a forthcoming paper (Qiu *et al.*, in prep.), we will present a detailed X-ray spectroscopic study of the system outside eclipse, in eclipse, and during egress. We will also discuss possible origins of the system (via a common envelope phase), and whether the primary is more likely to be a NS or a BH. Finally, we will show that phasing the sharp ingress of the eclipse over 20 years of archival observations can already reveal a period derivative (more exactly, a slow increase of the period). In turns, this can constrain for example whether most of the mass lost by the Wolf-Rayet donor ends up accreted by the compact object or ejected in a wind.

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