The ephemeris, orbital decay, and masses of 10 eclipsing HMXBs

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\textbf{ABSTRACT}

We take advantage of more than 10 years of monitoring of the eclipsing HMXB systems LMC X-4, Cen X-3, 4U 1700-377, 4U 1538-522, SMC X-1, IGR J18207-2016, Vela X-1, IGR J17252-3616, XTE J1855-026, and OAO 1657-415 with the ASM on-board RXTE and ISGRI on-board INTEGRAL to update their ephemeris. These results are used to refine previous measurements of the orbital period decay of all sources (where available) and provide the first accurate values of the apsidal advance in Vela X-1 and 4U 1538-522. Updated values for the masses of the neutron stars hosted in the ten HMXBs are also provided, as well as the long-term lightcurves folded on the sources best determined orbital parameters. These lightcurves reveal complex eclipse ingress and egresses, that are understood mostly as being due to the presence of accretion wakes. The results reported in this paper constitute a database to be used for population and evolutionary studies of HMXBs, as well as theoretical modelling of long-term accretion in wind-fed X-ray binaries.

\textbf{Key words.} binaries: eclipsing - pulsars: individual – stars: neutron – X-ray: binaries

1. Introduction

High-mass X-ray binaries (HMXB) are among the brightest X-ray sources in our Galaxy, and were discovered for the first time with the Uhuru satellite (Giacconi et al. 1971) and independently with balloon-borne instruments (see, e.g., Lewin et al. 1971). These sources typically host a compact object (often a neutron star, NS) accreting material lost by a massive companion. Depending on the nature of the latter star, HMXBs are divided into Be or Supergiant X-ray binaries (SgXBs). In the first case, a conspicuous X-ray emission is generated due to the accretion of the matter from the dense decretion disk around the companion star, that leads to transient events (outbursts) of different types (see, e.g., Reig 2011, for a review). In the SgXBs, the compact object can either accrete through the fast and dense wind produced by the companion, or in a few cases through the so-called Roche-lobe overflow (a number of systems showed evidence for both mechanisms contributing to the accretion onto the compact object and the overall X-ray emission; see, e.g., Chaty 2011, for a recent review).

In Roche-lobe accreting systems, the inflowing material from the companion star is endowed with a high specific angular momentum, and thus accretion is generally mediated by a disk surrounding the compact object. As this is a very efficient way to accrete matter, disk-fed systems achieve usually a strongly variable X-ray emission, reaching values significantly lower than those attained by disk-accreting system (ranging from $10^{34}$ to $10^{36}$ erg s$^{-1}$; see, e.g., Joss & Rappaport 1984; Nagase 1996; Bildsten et al. 1997).

Since their discovery, HMXBs have been intensively monitored in order to test wind accretion models onto magnetized NSs (see e.g., Lamers et al. 1976; Bhattacharya & van den Heuvel 1991; Lutovinov et al. 2013, and references therein), measure the long term spin-variation of NSs as function of the mass accretion rate (probing the so-called “accretion-torques”, see e.g., Ghosh & Lamb 1979; Lovelace et al. 1995), and study the evolution of the orbital parameters of these system through, e.g., measurements of the orbital period decay (see Bildsten et al. 1997 and references therein). In the majority of HMXBs, pulsations in the X-ray emission firmly established the presence of NSs as accreting compact objects (see, e.g., Lutovinov et al. 2005; Lutovinov & Tsygankov 2009, for a recent review and HMXBs statistic), and the detection of cyclotron absorption spectral features permitted the direct measurement of their magnetic field strength (~ $1 - 5 \times 10^{12}$ G; see, e.g., Coburn et al. 2002; Filippova et al. 2005; Caballero & Wilms 2012). In the HMXBs that did not show clear evidence of pulsations, the presence of black holes companions cannot still be firmly ruled out (see, e.g., the case of 4U 1700-377, Rubin et al. 1996; Clark et al. 2002).

Among more than hundred HMXBs, only in a few sources the inclination of the system is high enough that the compact star is periodically occulted along our line of sight by the companion, giving rise to X-ray eclipses. For these sources, it is possible to infer a number of orbital parameters (e.g., orbital period) from the measured duration of the eclipse. The energy-dependent profile of the X-ray lightcurve during the eclipse ingress and egress also reveal details of the OB stellar wind structure (e.g., White...
The 10 eclipsing HMXBs in ascending order of the orbital period. Where relevant, we indicated in brackets the uncertainties on the last digits of each reported value.

| Source       | Type     | Orbital Epoch | $P_{ch}$ | $P_i$ | $P_{orb}/P_{ch}$ | $a_i \sin i$ | $e$ | $\omega$ |
|--------------|----------|---------------|---------|------|-----------------|-------------|-----|----------|
| LMC X-4      | O9III    | 51110.86579(10) | 1.408397/62(26) | 13.5 | -0.987(7) | 26.343(16) | 0.006(2) | -         |
| Cen X-3      | O6(7-9)III | 50506.788423(7) | 2.087113996(7) | 4.8 | -1.799(2) | 39.6612(9) | < 0.0016 | -         |
| 4U 1700-37    | O6.5Iaf+  | 48900.373(15) | 3.411581(7) | -    | -3.0(6) | 48.82(2) | 49(11) | -         |
| 4U 1735-22    | B0.2Ia   | 52851.33(1) | 3.728382(11) | 526.8 | -0.18(1) | 10(12) | -         | -         |
| SMC X-1      | B0.5Ib   | 50354.972186(8) | 3.8922099(4) | 0.7 | -5.80(2) | 55.4876(0) | 0.00089(0) | 166(12) |
| SAX J1802.7-2017 | B1Ib | 52168.26(4) | 4.5696(9) | 139.6 | -48(1) | 68(1) | -         | -         |
| XTE J1855-026 | B0Iaep   | 51945.22(2) | 6.0724(9) | 560(7) | -    | 80(14) | 0.94(2) | 226(15) |
| Vela X-1     | B0.5Ic   | 48885.2189(12) | 8.9643690(4) | 285.2 | -15.89(13) | 0.0898(12) | 152.59(92) | -         |
| EXO 1722-365 | B0-B1Ia  | 53761.68(4) | 9.7403(4) | 413.9 | -    | 101(1) | < 0.19 | -         |
| OAO 1657-415 | B0-5Ig   | 50689.116(30) | 10.4474495(5) | 57.3 | -5.80(15) | 106.10(2) | 0.1033(6) | 87.6(14) |

Notes: [Levine et al. 2000; Bildsten et al. 1997]. [Levine et al. 1997]. [Raicher & Paul 2010]. [Rubin et al. 1996]. [Hammerschlag-Hensberge et al. 2003]. [Mukherjee et al. 2006]. [Clark 2000]. [Inam et al. 2010]. [Raicher & Paul 2010]. [Rubin et al. 1996]. [Zurita Heras et al. 2006]. [Thompson et al. 2007]. [Manousakis & Walter 2011]. [Baykal et al. 2011]. [Jenke et al. 2011]. [Hammerschlag-Hensberge et al. 2003]. [Bildsten et al. 1997]. [Chakrabarty et al. 1993]. 

The spin period of the NS (possibly) hosted in 4U1700-377 is currently unknown.

For the two HMXBs EXO 1722-365 and SAX J1802.7-2017, we indicated in Table 1 also the associated INTEGRAL source name IGR J17252-3616 and IGR J18027-2016, respectively [Zurita Heras et al. 2006]. These two sources are classified as highly absorbed HMXBs (see e.g., Walter et al. 2006) and indeed these are the only sources in which no eclipse is evident from their soft X-ray lightcurves (<12 keV, see Sec. 4).

The 10 selected sources comprise both disk and wind accreting systems. A different shape of the eclipse ingress and egress is expected in these two cases as a function of the energy (see Fig. 4). The relatively large X-ray luminosity of LMC X–4, Cen X–3, and SMC X–1 makes these sources the prime candidates for being disk-fed systems whereas 4U 1700–377, 4U 1538–522, SAX J1802.7–2017, XTE J1855–026, Vela X–1, and EXO 1722–363 are all thought to be wind-fed systems. OAO 1657–415 is unique among the known HMXBs as it is believed to be a wind-fed system for most of the time, and undergo only sporadically episodes of accretion from a temporary disk. Since the binary is too wide for Roche lobe overflow to occur, this may provide the first clear evidence that winds in HMXBs possess sufficient angular momentum to form accretion disks (see e.g., Bildsten et al. 1997). Chakrabarty et al. 1993).

Further additional information on the ten sources can be found in Liu et al. 2006.

2. Observations and data

All the eclipsing HMXBs reported in Table 1 have been continuously monitored in the X-ray domain by the ASM since the beginning of 1996 and by the IBIS/ISGRI since the early 2003. We used public available IBIS/ISGRI lightcurves retrieved from the on-line tool High-Energy Astrophysics Virtually ENlightened Sky (HEAVENS) or HEAVENS data reduction was performed using the standard Offline Science Analysis (OSA) version 9.0 distributed by the INTEGRAL Science Data Center (Courvoisier et al. 2003). For each source we downloaded the ISGRI high energy lightcurve binned over each pointing (science window).
of roughly 2 ks, in the 17–40 keV and 40–150 keV band. The RXTE/ASM lightcurves have been retrieved from the NASA HEARSCFT server[1] binned dwell-by-dwell (90 s bins) in the 1.5–3 keV, 3–5 keV, and 5–12 keV energy bands. In Table[2] we report the observation time interval and the total effective exposure time of the ASM and ISGRI data for each of the selected source. All the photons arrival times of the INTEGRAL/ISGRI and RXTE/ASM lightcurves were corrected to the barycenter reference time of the solar system. We used the OSA task barycent for the ISGRI data, and the procedure described in the RXTE cookbook[3] for the ASM data. The barycentric correction is usually considered mainly to perform highly precision timing analysis on a short observational time interval. However, in the present case, it was required in order to ensure uniformity over a long-term set of data spanning more than a decade.

For each of the eclipse found in the ISGRI and ASM lightcurves we measured the ingress, egress and the mid-eclipse time as described in Sec. 3.1.

### Table 2. Log of INTEGRAL/ISGRI and RXTE/ASM observations of the 10 selected eclipsing HMXBs.

| Source     | ISGRI (MID-50000) | Exp. (ks) | ASM (MID-50000) | Exp. (ks) |
|------------|-------------------|----------|-----------------|----------|
| LMC X-4    | 2641.40–5005.48   | 695      | 87.30–5748.11   | 5627     |
| Cen X-3    | 2650.54–5155.90   | 2033     | 87.29–5747.29   | 5297     |
| 4U 1700-377| 2688.25–5256.35   | 2863     | 88.11–5749.81   | 4709     |
| 4U 1538-522| 2650.74–5256.37   | 2285     | 88.11–5749.69   | 5494     |
| SMC X-1    | 2643.66–5008.01   | 704      | 88.35–5747.51   | 5405     |
| SMC X-1    | 2608.16–5256.18   | 4037     | 84.24–5744.55   | 2767     |
| XTE J1855-026| 7041.14–5153.06   | 2482     | 88.37–5749.75   | 5409     |
| Vela X-1   | 2644.45–5150.95   | 1665     | 87.29–5747.53   | 6317     |
| EXO 1722-363| 2668.25–5256.35   | 4147     | 88.11–5749.81   | 4657     |
| OAO 1657-415| 2668.25–5256.37   | 2353     | 91.13–5747.53   | 5065     |

### 3. Best fit ephemerides

#### 3.1. Orbital period and orbital period decay

For each of the selected sources we first determined the mid-eclipse (superior conjunction) times, $T_{\text{ecl}}$, of all the eclipses found in the ISGRI and ASM data by using the e-fold method. We then improved these values by fitting together the newly determined epochs together with those derived from earlier observations ($T_{\text{ecl}}$, see Appendix A and references therein) using the quadratic orbital change function:

$$T_n = T_0 + nP_{\text{orb}} + \frac{1}{2}n^2P_{\text{orb}}^2P_{\text{orb}}.$$

Here $P_{\text{orb}}$ is the orbital period in days, $P_{\text{orb}}$ is the period derivative at the epoch $T_0$ and $n$ is the integer number of elapsed binary orbits. All the new measured orbital ephemeris are reported in Table[5]. We show in Fig[4] the best fit models to the data obtained by assuming either a simple linear orbital evolution or including a quadratic orbital decay term (the residuals from these fits are also shown). For all those systems characterized by a non-negligible eccentricity ($\geq 0.1$), we fitted separately the mid-eclipse epochs, $T_{\text{ecl}}$, and the mean longitude, $T_{\text{orb}}$, epochs. For OAO 1657–415 we fit together the epochs of $T_{\text{ecl}}$ and $T_{\text{orb}}$ as the periastron angle of the source is known to be around 90° and therefore $T_{\text{ecl}} \equiv T_{\text{orb}}$ (see Sec. 3.2). All the least square fits in this work were performed by using the IDL tool MPFIT [Markwardt 2009]. We obtained in all cases $\chi^2_{\text{red}} \approx 1.0 – 1.3$.

In the case of the five sources LMC X-4, Cen X-3, 4U 1700-377, SMC X-1, and OAO1657-415 we measured a significant orbital period derivative (see Table[3]). For 4U 1538-522, the $P_{\text{orb}}$ value has been obtained excluding the mid-eclipse times derived from the Uhuru and Ariel lightcurves [Cominsky & Morasco 1991; Davison et al. 1977]. In the case of OAO 1657-415 we excluded the orbital epoch time reported by Barnstedt et al. [2008]. All these values were affected by relatively large uncertainties compared to the others and did not provide significant improvements to the fits. For the five sources characterized by a value of $P_{\text{orb}}$ consistent with zero (see Table[5]), the reported orbital epochs and periods were determined by using the linear orbital change function (see Eq. [1]).

#### 3.2. Apsidal advance

In eccentric orbits the time of mid-eclipse, $T_{\text{ecl}}$, determined from the eclipses in the X-ray lightcurves, and the time of mean longitude, $T_{\text{orb}}$, determined through the pulse arrival times technique, do not coincide. In this case we distinguished the orbital period, $P_{\text{orb}}$, defined as the time elapsed between two successive passages at the same mean-longitude $l = \pi$ and the eclipse period, $P_{\text{orb, ecl}}$, defined as the difference between two successive mid-eclipse epochs. The mean orbital longitude $l$ can be expressed as $l = M + \omega$, where $M$ is the mean anomaly and $\omega$ is the argument of periapsis. With the orbital relations, expressed in the first order of the eccentricity, the time delay between $T_{\text{ecl}}$ and $T_{\text{orb}}$ can be written as (see e.g., van der Klis & Bonnet-Bidaud 1984 and references therein):

$$T_{\text{orb}} - T_{\text{ecl}} = -\frac{P_{\text{orb, ecl}}}{P_{\text{orb}}} \cos \omega.$$

For an eccentricity of $e \approx 0.1$ and a periastron angle of $\omega \approx 150^\circ$ as in Vela X-1, this can result in a lag of 0.3 day. This periodic lag is zero for eccentric orbits if $\omega = 90^\circ$ and maximal when $\omega = 0$ or $180^\circ$. If the periastron angle $\omega$ is constant, then $P_{\text{orb, ecl}} = P_{\text{orb, ecl}}$. However, if the periastron is moving at a rate $\dot{\omega}$, the difference between $P_{\text{orb, ecl}}$ and $P_{\text{orb, ecl}}$ at the first order of its eccentricity, $e$, can be obtained by differentiating Eq. [2] (see Deeter et al. 1987):

$$P_{\text{orb, ecl}} - P_{\text{orb, ecl}} = \frac{P_{\text{orb}}}{P_{\text{orb}}} \omega \sin \omega.$$

Equations [2] and [3] allow estimating $\omega$ and $\dot{\omega}$ if $\sin \omega \neq 0$. For circular orbits we have $T_{\text{orb}} = T_{\text{orb}}$ and thus $P_{\text{orb, ecl}} = P_{\text{orb, ecl}}$. From Eq. [2] and the value of $\Delta P_{\text{obs}} = P_{\text{orb, ecl}} - P_{\text{orb, ecl}}$ determined from the observations, we calculated also the apsidal motion $\dot{\omega}$. The same epoch time is used to calculate both $(T_{\text{orb}}, P_{\text{orb, ecl}})$ and $(T_{\text{orb}}, P_{\text{orb, ecl}})$, as this time corresponds to the epoch of $\omega$ (see Table[1]).

Among the four sources with $e \gtrsim 0.04$ considered in the present work (see Table[1]) a detailed comparison of the measured epoch time lag $\Delta T_{\text{calc}} = e P_{\text{orb, ecl}} \cos \omega / \pi$ could not be carried out for OAO 1657-415 (its periastron angle is $\omega \approx 90^\circ$ and thus $T_{\text{orb}} \equiv T_{\text{orb}}$). XTE J1855-026 (only one $T_{\text{orb}}$ and $P_{\text{orb, ecl}}$ are available to date; see Appendix A) and EXO 1722-363 (no reliable eccentricity measurement is available in the literature; Thompson et al. 2007). For 4U 1538-522 we used the eccentricity, $e$, and the periastron angle, $\omega$, from Clark (2000) and Mukherjee et al.
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Table 3. Updated epochs, orbital periods, and period decay of the ten sources obtained by using all the available mid-eclipse times. We indicated in brackets the uncertainties at 1σ c.l. on the last digits of each reported value.

| Source         | $T_{\text{ocl}}$ (MJD) | $P_{\text{ocl}}$ (days) | $P_{\text{orb}}/P_{\text{ocl}}$ (10$^{-5}$ yr$^{-1}$) | $\omega$ (deg/yr) |
|----------------|------------------------|-------------------------|---------------------------------|------------------|
| LMC X-4        | 53013.59(10)           | 1.4087390(7)            | -1.00(5)                        | -                |
| Cen X-3        | 50506.788423(7)        | 2.08704106(3)           | -1.80(1)                        | -                |
| 4U 1700-377    | 53785.850(7)           | 3.411581(7)             | -1.6(1)                         | -                |
| 4U 1538-522$^a$ | 52855.061(13)          | 3.7284140(76)           | -0.7(8)                         | 1.3(6)           |
| SMC X-1        | 52846.68810(24)        | 3.891923160(66)         | -3.5(41)                        | -                |
| SAX J1802.7-2017$^a$ | 52168.245(34)       | 4.5697(1)               | -17(29)                         | -                |
| XTE J1855-026$^a$ | 52704.009(17)         | 6.07415(8)              | -12(13)                         | -                |
| Vela X-1$^b$   | 42611.349(13)          | 8.964427(12)            | -0.1(3)                         | 0.41(27)         |
| EXO 1722-363$^a$ | 53761.695(19)         | 9.74079(8)              | -21(14)                         | -                |
| OAO 1657-415   | 52674.1199(17)         | 10.447355(92)           | -3.4(1)                         | -                |

Notes. $^a$Epoch time and orbital period is derived from the linear fit; the orbital decay has been evaluated excluding the Uhuru and Ariel data. $^b$The orbital period derivative, $\dot{P}$, is consistent with zero and thus the epoch times and orbital periods are estimated using Eq. 1 (linear fit).

Table 4. In this table, the predicted $\Delta T_{\text{calc}}$ (Eq. 2), the measured epoch time lag, $\Delta T_{\text{obs}} = T_{\text{obs},\text{ocl}} - T_{\text{ocl}}$, and the orbital period lag, $\Delta P_{\text{obs}} = P_{\text{obs},\text{ocl}} - P_{\text{ocl}}$ are given for the two sources 4U 1538-522 and Vela X-1. The apsidal advance angle, $\omega$, is also reported. We indicated in brackets the uncertainties at 1σ c.l. on the last digits of each reported value.

| Source         | $T_{\text{ocl}}$ (MJD) | $T_{\text{obs,ocl}}$ (MJD) | $P_{\text{obs,ocl}}$ (day) | $\Delta T_{\text{obs}}$ (day) | $\Delta T_{\text{calc}}$ (day) | $\Delta P_{\text{obs}}$ (x10$^{-2}$) (yr) | $\omega$ (deg/yr) |
|----------------|------------------------|----------------------------|-----------------------------|-------------------------------|---------------------------------|------------------------------------------|------------------|
| 4U 1538-522$^a$ | 50450.234(11)          | 3.7284140(76)              | -0.011(15)                  | 0.0905(69)                    | 0.72(23)                        | 1.3(6)                                   | -                |
| 4U 1538-522$^a$ | 52704.009(17)          | 3.728337(22)               | -0.013(15)                  | 0.0905(69)                    | 0.72(23)                        | 1.3(6)                                   | -                |
| Vela X-1$^b$    | 42611.349(13)          | 8.964427(12)               | -0.1(3)                     | 0.41(27)                      | -                               | -                                        | -                |

Notes. $^a$The best fit values $T_{\text{ocl}}$ and $P_{\text{ocl}}$ were obtained including all the epochs available in the literature until the work of (the last one is reported by Clark [2000]). $^b$Same as before but using all epochs available until the work published by Mukherjee et al. (2006).

4. Folded lightcurves

The updated ephemerides we obtained for the ten HMXBs allowed folding their lightcurves with an unprecedented accuracy. We folded for each source the dwells RXTE/ASM light curves in the 1.3–3 keV, 3–5 keV, and 5–12 keV energy bands by using 128 phase bins (see Fig. 2 and 3). For LMC X-4, Cen X-3, 4U 1700-377, SMC X-1, and OAO 1657-415 the orbital period derivative was also taken into account during the folding. Given the values of $P_{\text{orb}}/P_{\text{ocl}}$ in Table 3 we obtained for these sources a maximum variance of the orbital period (between the first and last mid-eclipse time of the RXTE/ASM dataset) of ~ 0.088, 0.158, 0.139, 0.310, and 0.299 days, respectively. These delays have been calculated by using the quadratic term in Eq. 1 rewritten as $(\Delta t)^2 P_{\text{orb}}/P_{\text{ocl}}$ (we replaced $nP_{\text{orb}}$ by the observational elapsed time, $\Delta t$). The orbital derivatives for these sources are not negligible, as the derived correction factors in time are larger than a phase bin (1/128) and the inclusion of these corrections significantly improve the shape of the folded lightcurves.

The fluxes (cts/s) of the ten sources measured during the occultation of the compact object by the companion star are reported in Table 5. In all cases, the fluxes in the lower energy bands (1.3–3 keV, 3–5 keV, and 5–12 keV energy bands) are consistent with zero. This suggests that in the soft X-ray domain the source emission is strongly absorbed by the extended corona of the companion star, as well as from the companion star itself (in the literature, residual fluxes have been reported at a level that is too low to be detectable by the ASM on-board RXTE; see, e.g., Ebisawa et al. 1996; Lutovinov et al. 2000; Vrtilek et al. 2001). At higher energies (17–40 keV and 40–150 keV), the observed residual X-ray fluxes are most likely due to the presence of an extended X-ray scattering region (e.g., the accretion disc around the compact object, the X-ray irradiated surface of the companion star, or a cloud of material diffused around the system and produced by the intense wind of the supergiant star). These findings, together with the different shapes of the eclipse ingress and egress in Fig. 2 and 3 are discussed in Sect. 5.4.

4.1. Semi-eclipse angles

We used the folded lightcurves in the energy band 17–40 keV to estimate the semi-eclipse angle, $\theta_{\text{ocl}}$, of each eclipse observed from the ten selected sources in Table 1. In this energy band, all eclipses look sharp and symmetric, thus permitting to achieve an unprecedented accuracy in the determination of the occultation time (see Fig. 2 and 3). We followed the fitting method described in Rubin et al. (1996). The duration of each eclipse was calculated from the measured phase of the eclipse ingress and egress.
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The average phase $\phi_{(i,e)}$ (defined as the phase at which 99% of the source flux is occulted at eclipse ingress or egress) and the transition phase width $\tau_{(i,e)}$ were estimated by fitting independently the ISGRI light curve in the 17–40 keV and (whenever possible) in the 40–150 keV band with the function:

$$F_j = F_{\text{con}} \exp \left[ \ln(0.01) \exp \left[ -\left( \phi_j - \phi_{(i,e)} \right) / \tau_{(i,e)} \right] \right].$$

(4)

Here $j$ is the phase bin number and $F_{\text{con}}$ is the averaged count-rate of the source outside the eclipse determined prior to the fit. The 0.5–1.0 orbital phase was considered to fit the eclipse ingress and the 1.0–1.5 orbital phase was used for the egress. The duration of each X-ray eclipse for the ten sources was calculated as $\Delta \phi = (1.0 - \phi_1) + \phi$, in the (17–40 keV) band, thus providing the semi-eclipse angles, $\theta_e$, reported in Table 6 (all uncertainties are given at 1σ c.l.). We verified that the eclipse

Fig. 1. All measured mid-eclipses, $T_{\text{c,1}}$, mean longitudes, $T_{\pi/2}$, and orbital epochs are shown with the best fit models as a function of the orbit numbers. In all cases, the best fit model is a quadratic or linear fit to the epochs. The lower panel in each figure shows the residual from the best fit.
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Fig. 2. Folded lightcurves of the first 6 eclipsing HMXBs in Table 1. Data in the energy range 1.3-12 keV were obtained from the RXTE/ASM, while harder X-ray data are from INTEGRAL/ISGRI (17-150 keV). In all cases, the lightcurves have been folded by using the updated ephemerides obtained in the present work.

Table 5. Measured cts/s during the occultation phases of the ten selected sources in this work. Note that 0.2 cts/s (0.1 cts/s) in the 17–40 keV (40-150 keV) energy band in ISGRI correspond to roughly 1 mCrab. We indicated in brackets the uncertainties at 90% c.l. on the last digits of each reported value.

| Source            | 17 – 40 keV (cts/s) | 40 – 150 keV (cts/s) |
|-------------------|---------------------|----------------------|
| LMC X-4           | 0.9(1)              | 0.7(1)               |
| Cen X-3           | 0.27(8)             | –                    |
| 4U 1700-377       | 1.31(8)             | 0.50(6)              |
| 4U 1538-522       | –                   | –                    |
| SMC X-1           | 0.48(16)            | –                    |
| SAX J1802.7-2017  | 0.35(7)             | –                    |
| XTE J1855-026     | –                   | –                    |
| Vela X-1          | 1.02(7)             | 0.15(6)              |
| EXO 1722-363      | –                   | –                    |
| OAO 1657-415      | 0.60(7)             | 0.23(7)              |

All the semi-eclipse angles we measured and reported in Table 6 are a few degrees shorter than the values reported in the literature, the only two exceptions being 4U 1700-377 and LMC X-4. In the case of 4U 1700-377, our measured ingress phase is shorter than that measured by [Rubin et al., 1996], thus translating into a slightly longer eclipsing phase. For LMC X-4 our determined semi-eclipse angle of $\theta_e \approx 16^\circ$ is around half the value $\sim 27^\circ$ reported in the literature [Li et al., 1978]. This is most likely due to the very few number of eclipses available in the past and the different energy band used to estimate $\theta_e$ [White et al., 1978; Pietsch et al., 1985]. The usage of the long term observations available at present allow reducing the temporal variable distortions of the eclipse profile and provide a more reliable measurement of the semi-eclipse angle and eclipse duration.

5. Discussion

5.1. Masses of the 10 Neutron Stars

Determining the equation of state (EoS) of matter at densities comparable to those inside NSs is one of the most challenging problems of the modern physics and can only be addressed based on observations of astrophysical sources. Models proposed in the
past years can be tested against observational results especially evaluating the maximum NS mass that each EoS model is able to sustain (see e.g., Lattimer & Prakash 2001). Very soft EoSs predict maximum NS masses in the $1.4$–$1.5 M_{\odot}$ range (this occurs when the NS core is made by exotic matter as kaons, hyperons, and pions), whereas stiff EoSs can reach up to $2.4$–$2.5 M_{\odot}$. More massive NSs can thus provide stronger constraints on the EoSs. As discussed by Rappaport & Joss (1983), eclipsing HMXBs hosting X-ray pulsars provide a means to measure the NS mass and thus put constraints on their EoS.

In eclipsing HMXB the parameters needed to solve the equations that lead to the determination of the NS mass are: the system orbital period $P_{\text{orb}}$, the projected semi-major axis $a_{\text{s}} \sin i$, the eccentricity $e$, the periastron angle $\omega$, and the duration of the eclipse expressed as the semi-eclipse angle $\theta_{\text{e}}$ (see Sec. 4.1). The semi-amplitude of the NS radial velocity can be inferred from the results of timing analysis providing $K_{\text{s}} = 2\pi a_{\text{s}} \sin i / (P_{\text{orb}} (1 - e^2)^{1/2})$. The semi-amplitude of the radial velocity of the optical component, $K_{\text{opt}}$, can be determined by optical and/or UV spectra of this star (see Table 7). We note that the values of $K_{\text{opt}}$ determined through these techniques might be affected by uncertainties related to the companion star modelling see, e.g., Hammerschlag-Hensberge et al. 2003 Abubekerov 2004 Koenigsberger et al. 2012. The NS radial velocities, $K_{\text{s}}$, reported in Table 7 are inferred using the values of $a_{\text{s}} \sin i$, $e$, and $P_{\text{orb}}$ reported in Table 1 and 3. Two additional key parameters are required and can be estimated from theoretical arguments: (i) the Roche lobe filling factor $\beta$ (i.e., the ratio of the supergiant’s radius to that of its Roche lobe $\beta = R_{\text{opt}}/R_{\text{l}}$) and (ii) the ratio of the spin period of the supergiant to its orbital period $\Omega$.

For sake of completeness, we review below the main equations to determine the NS masses (see also Rappaport & Joss 1983). The masses of the optical supergiant companion, $M_{\text{opt}}$, and the neutron star, $M_{\text{s}}$, can be written in terms of the mass functions:

$$M_{\text{opt}} = \frac{K_{\text{s}}^3 P_{\text{orb}} (1 - e^2)^{1/2}}{2\pi G \sin^3 i} (1 + q)^2$$

The strong stellar wind, which is responsible for the mass transfer, makes the task of generating a radial velocity curve of the donor star difficult. Another issue that can result in difficulties is also when the compact companion heats up one side of the donor star, thereby distorting spectral line profiles, i.e., X-ray heating take place.

Fig. 3. Same as Fig. 2 but for the remaining 4 sources in Table 1.
and

\[ M_x = \frac{K_{\text{opt}}^2 P_{\text{orb}} (1 - e^2)^{3/2}}{2r G \sin^2 i} (1 + \frac{1}{q}), \]

(6)

where the mass ratio \( q \) is defined as \( q \equiv M_y/M_{\text{opt}} = K_{\text{opt}}/K_x \). Assuming a spherical companion star, the inclination angle of the system, \( i \), is found to be related to the semi-eclipse angle through the geometric relation:

\[ \sin i \approx \frac{\sqrt{1 - \beta^2 (R_L/a)^2}}{\cos \theta_e}. \]

(7)

We also made use here of the equation \( \beta = R_{\text{opt}}/R_L \). The ratio between the Roche lobe radius and the separation of the two stars, \( R_L/a \), can be approximated as (Joss & Rappaport 1984):

\[ \frac{R_L}{a} \approx A + B \log q + C \log^2 q, \]

(8)

where:

\[ A = 0.398 - 0.026\Omega^2 + 0.004\Omega^3 \]

\[ B = -0.264 + 0.0523\Omega^2 - 0.015\Omega^3 \]

\[ C = -0.023 - 0.005\Omega^2. \]

(9)

For HMXBs with circular orbits the ratio \( R_L/a \) is constant. When the orbit is eccentric the Roche Lobe filling factor, \( \beta \), is defined at the periastron, \( R_{\text{L}} \), and the separation between the centers of the two stars varies with the orbital phase. \( \beta \) in these cases, the separation between the centers of the two stars at mid-eclipse time is given by \( \beta = a(1 - e^2)/(1 + e \cos \omega) \), where \( \omega \) is the argument of periastron reported in Table 1. In our calculation the Roche lobe radius is estimated at the eclipse phase. The approximated Roche lobe radius, \( R_L \), is determined with an accuracy of about 2% over the ranges of \( 0 \leq \Omega \leq 2 \) and \( 0.02 \leq q \leq 1 \) (Joss & Rappaport 1984). Once the full set of input parameters above are given, the values of \( i \), \( M_x \), \( M_{\text{opt}} \), \( a \), \( R_{\text{opt}} \), and \( P_{\text{orb}} \) can be determined at 1σ c.l. by means of Monte-Carlo (MC) simulations. Uncertainties on all parameters are evaluated in the simulations by assuming that their values follow a Gaussian distribution. We used a linear distribution for the Roche lobe filling factor, \( \beta \), spanning the range 0.9–1.0. Note that for all the HMXBs considered here it is known from their optical lightcurves that the supergiant stars hosted in these systems are nearly filling their Roche lobes (see e.g., Tjemkes et al. 1986, and references therein).

Following the technique described above, we first computed for the four sources with known \( \Omega \) (LMC X-4, Cen X-3, SMC X-1, and Vela X-1) the remaining output parameters reported in Table 1. In order to verify the reliability of this method, we compared the observational reported projected stellar rotation velocity, \( v_{\text{rot}} \sin i \), measurements with our calculated value using results in Table 1, and the following equation:

\[ \Omega = 0.02 \left( \frac{v_{\text{rot}} \sin i}{\text{km s}^{-1}} \right) \left( \frac{P_{\text{orb}}}{\text{days}} \right) \left( \frac{R_{\text{opt}}}{R_\ast} \right)^{-1} (1 - e^2)^{3/2}/(1 + e)^{3/2}. \]

(10)

In Table 2 we compare the calculated and measured \( v_{\text{rot}} \sin i \) values. These values agree well within the uncertainties. Based on these results, we assumed for the sources 4U 1538-522, SAX J1802.7-2017, XTE J1855-026, EXO 1722-363, and OAO 1657-415 a mean value of \( \Omega = 0.91(20) \). As these systems are not circularized, \( \Omega \) is unlikely to be too close to unity. If tides are efficient, then we might expect that the rotation of the donor is synchronized at periastron, where the tides are most effective (Hut 1981). In this case, the star’s angular velocity is larger than the orbital velocity at mid-eclipse, thus leading to \( \Omega \gtrsim 1 \). For this reason we increased the uncertainty on \( \Omega \) to include values slightly larger than unity.

4U 1700-377 was considered separately, as its projected semi-major axis \( a \sin i \) is unknown and thus the corresponding \( \Omega \) cannot be determined as we have done for all other sources. For this source, we first estimated \( \Omega \) from Eq. 10 by using the observationally measured value of \( v_{\text{rot}} \sin i \), \( P_{\text{orb}} \), and the companion star radius \( R_{\text{opt}} = 21.9(1.9)R_\ast \) (see Table 7 and Clark et al. 2002). We thus performed several MC simulations with a variable \( \Omega \), until the \( \Omega \) obtained from one of the simulations was compatible (to within the uncertainties) with the observational value. The outputs of this simulation were then used to fill all other relevant parameters for the source 4U 1700-377 in Table 7.

| Source       | \( v_{\text{rot}} \sin i \) \( \text{km s}^{-1} \) | \( v_{\text{rot}} \sin i \) \( \text{km s}^{-1} \) |
|--------------|-------------------|-------------------|
| LMC X-4     | 240(25)           | 257(9.7)          |
| Cen X-3     | 200(40)           | 204.8(8)          |
| 4U 1538-522 | 180(30)           | 224.9(7)          |
| SMC X-1     | 170(30)           | 178.0(8)          |
| SMC X-1     | 172(1.5)          | 178.0(8)          |
| Vela X-1    | 116(6)            | 130.3(2)          |

Notes: van der Meer et al. (2007), van Kerkwijk et al. (1995a, see reference therein), Reynolds et al. (1993), Zuiderwijk (1995). This work, using Eq. 10 and our results reported in Table 1 and Table 3.

Our findings on all neutron star masses for the considered HMXBs are summarized in Fig. 3 together with previously published values. The neutron star masses for LMC X-4, Cen X-3, 4U 1538-522, SMCX-1, and Vela X-1 are from Rawls et al. (2011), while the mass of the neutron star hosted in 4U 1700-377 is derived from Clark et al. (2002). The corresponding values for SAX J1802.7-2017, EXO 1722-363, and OAO 1657-415 are obtained from Mason et al. (2011, 2010, 2012). We note that our estimated uncertainties on the neutron star masses are somewhat more conservative than those reported by Rawls et al. (2011) and Mason et al. (2011, 2010, 2012). The reason behind these differences is that these authors derived their uncertainties either from analytical calculations or through numerical simulations including a particularly refined treatment for the Roche-Lobe size of the supergiant star. In the present work, all uncertainties are, instead, derived directly from the MC simulations and account for the most recently updated system parameters obtained from multi-wavelength observations. In particular, we reported for all sources in Table 6 the most accurately measured values of the semi-eclipse angles, which play a crucial role in the MC simulations. We note that in all cases our measured semi-eclipse angle is smaller than reported values in the literature (see Table 6), and thus the NS masses we estimated are generally larger. This seems reasonable especially for 4U 1538-522 and SMC X-1, as the NS masses estimated before where \( \lesssim 1M_\odot \). The only exception to this trend is 4U 1700-377, for which our estimated semi-eclipse angle is comparable to that obtained by Rubin et al. (1996).
Table 6. Best fit orbital profile parameters in units of the orbital phase. For each source we indicated with $\theta_e$ the semi-eclipse angle measured from our ISGRI lightcurves (17–40 keV energy band), $\phi_e$ is the defined as the phase at which 99% of the source flux is occulted at eclipse ingress or egress, and $\tau_e$ the corresponding transition phase width. The values of the semi-eclipse angles reported in the last column, $\theta_{old}$, are from the literature. We indicated in brackets the uncertainties at 1σ c.l. on the last digits of each reported value.

| Source     | $\phi_1$ | $\tau_1$ | $\phi_e$ | $\tau_e$ | $\theta_0$ (deg) | $\theta_{old}$ (deg) |
|------------|----------|----------|----------|----------|------------------|----------------------|
| LMC X-4   | 0.951(4) | 0.020(1) | 0.039(3) | 0.012(2) | 15.8(8)          | 27.2                  |
| Cen X-3   | 0.922(1) | 0.019(1) | 0.077(1) | 0.0187(6) | 27.9(3)          | 3(3)                  |
| 4U 1700-377 | 0.912(4) | 0.0185(5) | 0.0894(4) | 0.0126(2) | 32(1)           | 29.2                 |
| 4U 1538-522 | 0.936(4) | 0.018(2) | 0.052(4) | 0.0147(5) | 21(1)           | 29.2                  |
| SMC X-1   | 0.939(9) | 0.0139(4) | 0.066(5) | 0.007(2) | 23(2)           | 28(2)                  |
| SAX J1802.7-2017 | 0.94(1) | 0.038(9) | 0.11(1) | 0.012(7) | 31(2)           | 35.5                  |
| XTE J1855-026 | 0.920(5) | 0.0129(3) | 0.097(6) | 0.016(4) | 32(1)           | 42(6)                 |
| Vela X-1  | 0.9202(4) | 0.0209(1) | 0.0899(2) | 0.0084(2) | 30.5(1)         | 33(3)                  |
| EXO 1722-363 | 0.94(2) | 0.013(8) | 0.088(4) | 0.004(2) | 26(4)           | 32(3)                 |
| OAO 1657-415 | 0.933(1) | 0.0184(6) | 0.049(2) | 0.0352(1) | 20.9(4)         | 30(1)                 |

Notes: van der Meer et al. (2007) and references therein, Clark et al. (1988), Rubin et al. (1996), van Kerkwijk et al. (1995a), Hill et al. (2005), Corbet & Mukai (2002), van Kerkwijk et al. (1995b), Corbet et al. (2005), Chakrabarty et al. (1993).

Table 7. Input and output parameters for the MC simulations used to finally estimate the mass of the NSs hosted in the 10 HMXBs considered in this work. We indicated in brackets the uncertainties at 1σ c.l. on the last digits of each reported value.

| Source     | Input $K_x$ | $K_{opt}$ | $q$ | $\Omega$ | Output $t$ | $M_{NS}$ | $L_{opt}$ | $K_{opt}$ | $R_{L}/a$ | $a$ |
|------------|-------------|-----------|-----|---------|-----------|----------|----------|----------|----------|-----|
| LMC X-4   | 407.3(3)    | 35(2)     | 0.86(4) | 0.97(5) | 59.3(9)   | 0.95(11) | 18(1)   | 7.4(4)   | 0.59(1) | 14.22 |
| Cen X-3   | 414.317(9)  | 28(2)     | 0.06(6) | 0.75(13) | 65(1)     | 1.57(16) | 24(1)   | 11.4(7)  | 0.63(1) | 20.2(4) |
| 4U 1700-377 | 435(10)    | 19(1)     | 0.04(3) | 0.47(14) | 62(1)     | 1.96(19) | 46(5)   | 22(2)   | 0.69(4) | 35(1) |
| 4U 1538-522 | 316(10)    | 20(3)     | 0.06(1) | 0.91(20) | 67(1)     | 1.02(17) | 16(2)   | 13(1)   | 0.53(3) | 22(1) |
| SMC X-1   | 299.635(1)  | 20(1)     | 0.06(4) | 0.91(20) | 62(2)     | 1.21(12) | 18(2)   | 15(1)   | 0.61(2) | 27.9(4) |
| SAX J1802.7-2017 | 324(2) | 24(3)     | 0.07(1) | 0.91(20) | 72(2)     | 1.57(25) | 22(2)   | 18(1)   | 0.61(2) | 33(1) |
| XTE J1855-026 | 289(5) | 20(3)     | 0.07(1) | 0.91(20) | 71(2)     | 1.41(24) | 21(2)   | 22(2)   | 0.63(3) | 40(1) |
| Vela X-1  | 278.1(3)    | 23(2)     | 0.08(15) | 0.67(4) | 72.8(4)   | 2.12(16) | 26(1)   | 29(1)   | 0.59(6) | 59.6(4) |
| EXO 1722-363 | 226(2)    | 25(5)     | 0.11(2) | 0.91(20) | 68(2)     | 1.91(45) | 18(2)   | 26(2)   | 0.58(3) | 52(2) |
| OAO 1657-415 | 222(60)   | 21(4)     | 0.09(1) | 0.91(20) | 67(9)     | 1.74(30) | 17(5)   | 25(2)   | 0.52(2) | 53.1(4) |

Notes: van der Meer et al. (2007), Hammerschlag-Hensberge et al. (2003), Mason et al. (2011), Quaintrell et al. (2003), van Kerkwijk et al. (1995a, see reference therein), van Kerkwijk et al. (1995a), Hill et al. (2005), Corbet & Mukai (2002), van Kerkwijk et al. (1995b), Corbet et al. (2005), Chakrabarty et al. (1993).

5.2. Orbital period change

Five out of the 10 HMXBs analyzed in the present work showed evidence for a significant orbital period decay, i.e., LMC X-4, Cen X-3, 4U 1700-377, SMC X-1, and OAO 1657-415 (our values can be compared with previous measurements published in the literature by using the references reported in the Tables in Appendix A). For all these sources, a number of different mechanisms to explain the orbital period decay has been invoked (see e.g., Kelley et al. (1983), van der Klis (1983), van der Klis & Bonnet-Bidaud (1984), Levine et al. (1993), Rubin et al. (1996), Safi Harb et al. (1996), Levine et al. (2000), Jenke et al. (2011)). The hypothesis that the period change is due entirely to angular momentum loss in the stellar wind, i.e. mass transfer without interaction, can be ruled out. More realistic models proposed that the orbital decay is mostly driven by the tidal interaction and the rapid mass transfer between the two objects. The latter takes place due to the fast winds that characterize most of the donor stars in HMXBs. In these models, the asynchronism between the orbit and the rotation of the donor star is maintained by the evolutionary expansion of the donor star (see e.g., Lecar et al. (1976), Safi Harb et al. (1996), Levine et al. (2000), van der Klis & Bonnet-Bidaud (1984) and references therein). If the donor star is rotating with an angular velocity close to synchronization, the matter ejected leaves the system and carries an extra momentum due to this rotation. This loss of rotational momentum affects the orbital period only if there is a coupling between the rotation of the donor star and the orbit of the neutron star. Tidal interactions could synchronize the orbit with the rotation of the donor star and allow the transfer of rotational momentum of the primary star to the orbital momentum. Tidal effects on the radial velocity curve of the donor star in Vela X-1 have been investigated deeply, but not final conclusions could be drown due to the limited quality of the data (Koenigsberger et al. 2012). Tidal interactions in close binary systems has been investigated in detail also theoretically by using different approaches, e.g., assum-
ing the rotation of the donor star is synchronized or pseudosynchronized, with the orbit motion of the compact star (see e.g., Moreno et al. 2011; Hut 1981; Zahn 1977; Lecar et al. 1976). A number of other works argued that the combined effects of the evolutionary growth of the moment of inertia (expansion of the donor star) and mass loss by stellar wind from a donor star can explain the orbital decay in HMXBs (Bagot 1996; Levine et al. 1997). In these models, it is considered that, as the companion star evolves, it expands and increases its moment of inertia, leading to a slow down of the star rotation. Tidal torques would then transfer orbital angular momentum to synchronize the binary system, finally causing an orbital decay (see e.g., Levine et al. 1993; references therein). As the lifetime of a supergiant star does not exceed a few $10^6$ yr, we expect that most of the systems considered in this work are nearly synchronized but not fully circularized yet. This is in agreement with the non-negligible values of the eccentricity measured in some of the eclipsing HMXBs (see Table 1).

The updated and newly reported estimates of the orbital periods decay of the ten HMXBs considered in the present work can be used as inputs in future works on these topics. We expect that this might help discriminating among the different mechanisms proposed to explain the orbital period decay in HMXBs and to estimate their orbital circularization and synchronization timescales, as well as to discuss the Darwin instability (see e.g., Lai et al. 1994) for these systems. Additional calculations on all these effects are beyond the scope of the present paper.

In order to help future works to evaluate numerically different theoretical models, we finally report for reference also the stellar wind velocities and mass loss rates of all sources considered in this paper in Table [9]. These have been calculated by assuming the spectral types reported in Table [1] and in Table [2] we indicate both the terminal wind velocities inferred from observations in the literature and those calculated theoretically. For the latter we followed Martins et al. (2005) and Kudritzki & Puls (2000) for O-stars, and Markova & Puls (2008), Crowther et al. (2006), Lefever et al. (2007) for B-stars. In all cases, the nominal mass loss rates have been reduced by a factor of 3 in order to account for clumping and uncertainties on the terminal wind velocities are assumed to be at the 30% (Markova & Puls 2008; Repolust et al. 2004). As all data in Table [9] have been calculated assuming that the wind is emitted by an isolated massive star, it is possible that in a number of systems the disturbance of the neutron star lead to substantially different wind properties. Detailed numerical simulations have showed that this could be the case especially for short orbital period systems with high X-ray luminosities (Watanabe et al. 2006; Manousakis et al. 2014). Unfortunately, direct measurements of the wind properties for the systems considered here are challenged by the relatively high absorption local to the sources and their large distance (Chaty 2013).

### 5.3. Apsidal motion

Beside asteroseismology (see, e.g., Dupret et al. 2011; references therein), the measurement of the apsidal advance in eccentric binary systems offer an alternative possibility to investigate the internal structure of stars compared to theoretical calculations and numerical modelling. The rate at which the longitude of periastron of an eccentric orbit advances can be related to the apsidal motion constant, which depends on the model of the mass distribution inside the star (Kopal 1978; Batten 1973). X-ray pulsars in HMXBs have been far considered the most promising laboratories to measure accurately the apsidal advance. The neutron star in these systems can be considered as a point source with a negligible apsidal motion constant compared to that of the massive companion. The latter is thus dominating the apsidal advance (Rappaport et al. 1980).

The long term analysis carried out in this paper, allowed us to provide the most accurate apsidal advance measurement for Vela X-1 and 4U 1538-522. (note, however, that for the former source the measurement is only marginally significant at 1.5$\sigma$.)

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**Table 4.** The masses of the ten eclipsing HMXBs. The neutron star masses determined in this work are shown with solid lines. Values from the literature are represented with dashed lines. The error bars correspond to uncertainties at 1$\sigma$ c.l. The dashed vertical line indicate the canonical neutron star mass of 1.4 M$_\odot$.

| Source     | $M_{\odot}$ Observed | $M_{\odot}$ Theoretical | $M_{\odot}$ yr$^{-1}$ Theoretical |
|------------|----------------------|-------------------------|-----------------------------------|
| LMC X-4    | 1.40 (0.10)          | 1.40                     | 1.40                              |
| Cen X-3    | 1.40 (0.10)          | 1.40                     | 1.40                              |
| 4U 1700-377| 1.40 (0.10)          | 1.40                     | 1.40                              |
| 4U 1538-522| 1.40 (0.10)          | 1.40                     | 1.40                              |
| SMC X-1    | 1.40 (0.10)          | 1.40                     | 1.40                              |
| SAX J1802.7-2017| 1.40 (0.10) | 1.40                     | 1.40                              |
| XTE J1855-026| 1.40 (0.10)        | 1.40                     | 1.40                              |
| Vela X-1   | 1.40 (0.10)          | 1.40                     | 1.40                              |
| EXO 1722-363| 1.40 (0.10)         | 1.40                     | 1.40                              |
| OAO 1657-415| 1.40 (0.10)         | 1.40                     | 1.40                              |

**Table 9.** Properties of the stellar winds in the 10 HMXBs considered in this paper as inferred from observations and theoretical calculations.

| Source     | $v_{\infty}$ km s$^{-1}$ Observed | $v_{\infty}$ km s$^{-1}$ Theoretical | $M_{\odot}$ yr$^{-1}$ Theoretical |
|------------|-----------------------------------|-------------------------------------|-----------------------------------|
| LMC X-4    | 1300 (350)                        | 1950 (600)                          | 2.4 (10^{-7})                     |
| Cen X-3    | 900 (300)                         | 1000 (300)                          | 8.3 (10^{-7})                     |
| 4U 1700-377| 1700 (100)                        | 1850 (550)                          | 2.1 (10^{-6})                     |
| 4U 1538-522| 870 (260)                         | 870 (260)                           | 1.5 (10^{-4})                     |
| SMC X-1    | 600 (200)                         | 600 (200)                           | 6.3 (10^{-7})                     |
| SAX J1802.7-2017| 600 (200) | 600 (200)                           | 6.3 (10^{-7})                     |
| XTE J1855-026| 600 (200)                       | 600 (200)                           | 6.3 (10^{-7})                     |
| Vela X-1   | 600 (200)                         | 600 (200)                           | 6.3 (10^{-7})                     |
| EXO 1722-363| 600 (200)                        | 600 (200)                           | 6.3 (10^{-7})                     |
| OAO 1657-415| 600 (200)                        | 600 (200)                           | 6.3 (10^{-7})                     |

**Notes.** References: [1] Boroson et al. (1999); [2] Wojslawski et al. (2003); [3] van Loon et al. (2001); [4] No consolidated measurement available in the literature - at the best of our knowledge; [5] Mason et al. (2012).
In the case of Vela X-1, the theoretical estimated apsidal motion is $\omega \sim 0.4$ yr$^{-1}$, assuming a companion star surface temperature of 25000 K (as predicted accordingly to its spectral type; see, e.g., Avni & Bahcall 1975 [Conti 1978]). The measurement reported in Table 2 is thus fully consistent with the theoretical expected value (see Deeter et al. 1987 and references therein). To the best of our knowledge, this is the first time that such match is reported, given the reduced uncertainty on the measured value of $\omega$ (even though this is still only marginally significant).

In the case of 4U 1538-522, no firm measurement of the apsidal motion was reported in the literature. We notice that the tentative value provided by Mukherjee et al. (2006) was estimated by comparing only two measurements of $\omega$ collected in 1997 and 2003 and thus is not comparable to the refined estimate reported in the present work. Our measurement thus provides the first consolidated estimate of $\omega$ for 4U 1538-522.

### 5.4. Eclipse asymmetry

The updated ephemeris for all the 10 HMXBs in Table 2 that we obtained in this work allowed us to fold with an unprecedented accuracy the long term ASM and ISGRI lightcurves of these objects in different energy bands. The results are shown in Fig. 2 and 3. The available broad-band energy coverage permitted to study in detail the averaged profile of the eclipse ingress at egress for each object. We note that in the case of SAX J1802.7-2017, XTE J1855-026, and EXO 1722-363, this study could not be easily carried out at low energies due to the strong absorption affecting the X-ray emission from these sources (this is expected according to their classification as “highly obscured HMXBs”; see, e.g., Chaty 2013 for a recent review). In most of the other sources we found peculiar asymmetries that are more pronounced at the lower energies and slightly more enhanced in objects characterized by a non-negligible eccentricity. Remarkable asymmetries are recorded for the eclipse ingress and egresses of 4U 1700-377 and Vela X-1. Evident eclipse asymmetries are also displayed by 4U 1538-522 and OAO 1657-415.

In most of the sources considered in this work, single eclipse profiles have been studied in the past by using focusing X-ray instruments capable of high resolution spectroscopy (e.g., XMM-Newton and Chandra; see Watanabe et al. 2006 and references therein). These observations proved to be particularly powerful to analyze how the X-ray emission from HMXBs is affected by the presence of inhomogeneities in the stellar winds (Sako et al. 2003). Such inhomogeneities (“clumps”; see e.g., Puls et al. 2008 for a recent review) are transported away from the star with typical velocities of a smooth wind and thus can induce changes in the mass accretion rate (and X-ray luminosity) on timescales as short as 100-1000 s. The feedback of X-ray radiation is also known to affect the structure of the wind on similar timescales, as high energy photons ionize the metal ions in the wind and dramatically reduce the wind acceleration mechanism (in turns affecting the velocity and density profile of outflows from the massive stars).

The eclipse profiles we discussed above provide, instead, important information on the interaction between the compact object and the stellar wind on much longer timescales (e.g., yrs). The influence of wind inhomogeneities is in all cases averaged away by the long-term integration, and only the effect of X-ray irradiation on the wind averaged on hundreds of orbital revolutions can be observed from these curves. Under these assumption, we argue that the eclipse asymmetries are most likely due to the presence of “accretion wakes”. These structures are commonly observed in HMXBs and form as a consequence of the compact object intense gravity and conspicuous X-ray emission (see, e.g., Fig. 5 in Blondin et al. [1990] and Fig. 1-5 in Manousakis et al. [2012]).

As the accretion wake usually trails the neutron star during its orbital revolution around the companion and can lead to an increase of the wind density around the compact object by a factor of $\sim 10-100$ (Manousakis et al. 2014), it is expected that absorption column density in the direction of the X-ray source progressively increases before the occurrence of the X-ray eclipse. During the egress from the eclipse, the accretion wake is located beyond the compact object along the line of sight to the observer and thus do not lead to any apparent increase of the local absorption column density.

An interesting possibility is also that this effect is enhanced in systems endowed with a non-negligible orbital eccentricity due to the different degree of ionization of the stellar wind material when the neutron star approaches or recedes from the companion. It is well known that in case of eccentric orbits, the absolute value of the vector sum of the neutron star orbital velocity and the stellar wind velocity reaches a minimum while the compact object approaches the companion, and then increases toward the upper conjunction (see, e.g., Ducci et al. 2010 and references therein). In a wind accreting system, the amount of material that a neutron star can capture from the companion at any time is roughly comparable to $\pi R_{\text{acc}}^2$, where $R_{\text{acc}} \approx \frac{2GM_{\text{NS}}}{v_{\text{rel}}^2}$ (11) and $v_{\text{rel}}$ is the relative velocity mentioned above. It is thus expected that a larger X-ray luminosity is released at lower values of $v_{\text{rel}}$ due to the enhanced accretion rate (see, e.g., Bozzo et al. 2008 and references therein). As the ionization of the wind is proportional to the X-ray flux and acts to substantially inhibit the wind acceleration mechanism, a larger density would also be expected around a bright X-ray emitting neutron star approaching the companion. Furthermore, the X-ray flux could be evaporating additional material from the massive star around this orbital phase, possibly enhancing the absorption column density in the direction of the source during the eclipse ingress (Blondin & Woo 1995). We note that in short orbital period systems, the formation of (at least) temporary accretion disks when the neutron star is at the closest distance from the companion could also provide enhanced accretion rates and thus positively contribute to increase the mass density around the neutron star (e.g., Ducci et al. 2010). A quantitative estimate of all these effects would require more detailed calculations combining also the effect of the neutron star spin and magnetic field.

### 6. Conclusions

In this work, we performed orbital mid-eclipse time measurements on the ten known eclipsing HMXBs using publicly available pre-processed RXTE/ASM and INTEGRAL/ISGRI data. For each source, we determined several new orbital mid-eclipse times and used them together with all previously published value (to the best of our knowledge) to obtain the most updated and homogeneous set of ephemerides to date. The latter allowed us in particular to update the orbital periods of all the 10 binaries, as well as the decay of these periods. In five sources (LMC X-4, Cen X-3, 4U 1700-377, SMC X-1, and OAO 1657-415) we measured a significant orbital period decay, with values in the range $1.0 - 3.5 \times 10^{-6}$ yr$^{-1}$; in all other case no significant decay was revealed even though more than 30 yrs of X-ray observations

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Appendix A: Ephemeris tables

| Epoch Time (MJD) | Satellite | Reference |
|------------------|-----------|-----------|
| 42829.494(19)    | EXOSAT    | Kelley et al. (1983) |
| 45651.917(15)    | EXOSAT    | Dennerl (1991) |
| 45656.1453(8)    | EXOSAT    | Dennerl (1991) |
| 46447.668(11)    | EXOSAT    | Dennerl (1991) |
| 46481.467(3)     | EXOSAT    | Dennerl (1991) |
| 47229.3313(4)    | Ginga     | Woo et al. (1990) |
| 47741.9904(2)    | Ginga     | Levine et al. (1990) |
| 48558.8598(13)   | ROSAT     | Woo et al. (1990) |
| 51478.454(8)     | RXTE/ASM  | Levine et al. (2000) |
| 51110.86579(20)  | RXTE      | Levine et al. (2000) |
| 52648.813(14)    | INTEGRAL  | Present Work |
| 53013.590(14)    | INTEGRAL  | Present Work |
| 53016.40(2)      | INTEGRAL  | Present Work |
| 54262.825(8)     | RXTE/ASM  | Present Work |

were used. For the eccentric systems Vela X-1 and 4U 1538-522 we accurately determined for the first time a significant apsidal advance, comparing it with previously expected values.

Using our best estimated mid-eclipse epoch, orbital period, and period derivative for each source, we folded the lightcurves of the ten binaries obtained from the long-term monitoring carried out with the ASM on-board RXTE (1.3-12 keV) and ISGRI on-board INTEGRAL (17-150 keV). We discussed the asymmetric profiles of the eclipse ingresses and egresses, comparing them with theoretical expectations from simulations of accreting wind-fed systems.

Finally, we used all above mentioned results within the MC simulations to consistently and systematically evaluate the masses of the NS hosted in the 10 eclipsing HMXBs. The results reported in this paper constitute an important database for population and evolutionary studies of HMXBs, as well as theoretical modelling of long-term accretion in wind-fed X-ray binaries.

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### Tabular Data

#### 4U 1538-522

| Epoch Time | Satellite | Reference |
|------------|-----------|-----------|
| $T_{\text{ecl}}$ | RXTE | Becker et al. (1977) |
| 43015.8(1) | OXO-S | Becker et al. (1977) |
| 45517.668(50) | Tenma | Maksymian et al. (1987) |
| 47221.474(20) | Ginga | Corbel et al. (1993) |
| 48000.979(27) | BATSE | Rubin et al. (1997) |
| 49003.629(22) | BATSE | Rubin et al. (1997) |
| 49398.856(29) | RXTE | Rubin et al. (1997) |
| 49797.781(22) | BATSE | Rubin et al. (1997) |
| 50450.206(14) | RXTE | Clark (2000) |
| 52851.33(1) | RXTE | Mukherjee et al. (2006) |
| 52855.042(25) | RXTE | Bykai et al. (2006) |

#### RXTE/ASM

| Epoch Time | Satellite | Reference |
|------------|-----------|-----------|
| $T_{\text{ecl}}$ | RXTE/ASM | Present Work |
| 41449.95(7) | Uhuru | Cominsky & Morris (1991) |
| 42628.0(1) | Ariel-V | Davison et al. (1977) |
| 43258.35(10) | Ariel-V | Davison et al. (1977) |
| 43384.889(22) | HEAO-A1 | Cominsky & Morris (1991) |
| 43563.827(22) | HEAO-A1 | Cominsky & Morris (1991) |
| 45920.2(2) | EXOSAT | Cominsky & Morris (1991) |
| 45923.9(2) | EXOSAT | Cominsky & Morris (1991) |
| 51016.96(3) | RXTE/ASM | Present Work |
| 52702.22(3) | INTEGRAL | Present Work |
| 52877.4(3) | RXTE/ASM | Present Work |
| 53779.69(50) | INTEGRAL | Present Work |
| 54734.18(3) | RXTE/ASM | Present Work |
| 54868.37(5) | INTEGRAL | Present Work |

#### SMC X-1

| Epoch Time | Satellite | Reference |
|------------|-----------|-----------|
| $T_{\text{ecl}}$ | SAX J1802.7-2017 | Present Work |
| 40963.99(2) | Uhuru | Schroeter et al. (1973) |
| 42275.65(4) | Copernicus | Runyan & Regan (1975) |
| 42836.182(28) | SAS-3 | Priim et al. (1977) |
| 42999.6567(16) | Ariel 5 | Davison et al. (1977) |
| 43116.4448(22) | COS-B | Bonnet-Bidaud & van der Klis (1981) |
| 46942.4723(15) | Ginga | Levine et al. (1993) |
| 47401.744476(7) | Ginga | Levine et al. (1993) |
| 47740.359063(3) | Ginga | Levine et al. (1993) |
| 48534.347866(35) | ROSAT | Wijers et al. (1998) |
| 48892.4191(5) | ROSAT | Wijers et al. (1998) |
| 49102.59(9682) | ASCA | Wijers et al. (1998) |
| 49137.61911(5) | ROSAT | Wijers et al. (1998) |
| 50091.1706(63) | RXTE | Wijers et al. (1998) |
| 50324.69186(18) | RXTE/ASM | Rau & Paul (2010) |
| 50787.849(14) | RXTE/ASM | Present Work |
| 51694.67302(1) | RXTE | Rau & Paul (2010) |
| 52185.052(3) | RXTE/ASM | Present Work |
| 52846.700(25) | RXTE | Rau & Paul (2010) |
| 52979.017(1) | RXTE | Rau & Paul (2010) |
| 53582.268(14) | RXTE/ASM | Present Work |

#### EXO 1722-365

| Epoch Time | Satellite | Reference |
|------------|-----------|-----------|
| $T_{\text{ecl}}$ | OAO 1657-415 | Present Work |
| 51112.187(22) | RXTE | Thompson et al. (2007) |
| 51219.35(5) | RXTE | Corbet et al. (2005) |
| 52875.276(92) | RXTE | Thompson et al. (2007) |
| 53761.679(24) | RXTE | Thompson et al. (2007) |
| 53769.083(97) | XMM-Newton | Manousakis & Walter (2011) |

#### Vela X-1

| Epoch Time | Satellite | Reference |
|------------|-----------|-----------|
| $T_{\text{ecl}}$ | OAO 1657-415 | Present Work |
| 48590.6549(27) | BATSE | Jenke et al. (2011) |
| 48515.99(5) | BATSE | Chen & Barnes (1993) |
| 48547.3800(52) | BATSE | Jenke et al. (2011) |
| 48578.7293(50) | BATSE | Jenke et al. (2011) |
| 48735.4836(23) | BATSE | Jenke et al. (2011) |
| 49299.5094(62) | BATSE | Jenke et al. (2011) |
| 49623.4633(48) | BATSE | Jenke et al. (2011) |
| 50260.7701(26) | BATSE | Jenke et al. (2011) |
| 50292.1121(52) | BATSE | Jenke et al. (2011) |
| 50323.4677(31) | BATSE | Jenke et al. (2011) |
| 50354.8047(21) | BATSE | Jenke et al. (2011) |
| 50584.6562(45) | BATSE | Jenke et al. (2011) |
| 50689.116(50) | RXTE | Rau & Paul (2011) |
| 52663.893(10) | INTEGRAL | Burslem et al. (2006) |
| 54721.7660(30) | Fermi | Jenke et al. (2011) |
| 54753.1029(34) | Fermi | Jenke et al. (2011) |
| 55254.5552(25) | Fermi | Jenke et al. (2011) |
| 55306.7930(25) | Fermi | Jenke et al. (2011) |
| 55338.1441(31) | Fermi | Jenke et al. (2011) |
| 55526.1813(24) | Fermi | Jenke et al. (2011) |
| 55776.9135(38) | Fermi | Jenke et al. (2011) |

#### 4U 1538-522

| Epoch Time | Satellite | Reference |
|------------|-----------|-----------|
| $T_{\text{ecl}}$ | RXTE | Present Work |
| 52704.038(30) | INTEGRAL | Present Work |
| 54009.9725(50) | INTEGRAL | Present Work |
| 54890.6795(50) | INTEGRAL | Present Work |

#### Vela X-1

| Epoch Time | Satellite | Reference |
|------------|-----------|-----------|
| $T_{\text{ecl}}$ | RXTE/ASM | Present Work |
| 52674.138(60) | INTEGRAL | Present Work |
| 52705.4(1) | RXTE/ASM | Present Work |
| 53186.04(10) | INTEGRAL | Present Work |
| 53562.173(60) | INTEGRAL | Present Work |
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