Centaurus X-3 orbital ephemerides using Insight-HXMT, RXTE, Swift/BAT, and NuSTAR observations

Moritz Klawin¹, Victor Doroshenko¹, Andrea Santangelo¹, Long Ji², Lorenzo Ducci¹, Qing cui Bu¹, Shuang-Nan Zhang³,⁴, and Shu Zhang³

¹Institut für Astronomie und Astrophysik, Sand 1, 72076 Tübingen, Germany
²School of Physics and Astronomy, Sun Yat-Sen University, Zhuhai, China, 519082
³Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Beijing 100049, China
⁴University of Chinese Academy of Sciences, Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
e-mail: klawin@astro.uni-tuebingen.de

ABSTRACT

Centaurus X-3 (Cen X-3) is the first X-ray pulsar discovered and has been studied for decades by multiple facilities, allowing for accurate measurements of the decay rate of the orbital period of the binary system. However, the most recent study of the orbital parameters of the system dates back to the RXTE era. For this study, we have complemented these measurements with the more recent high-quality Insight-HXMT and NuSTAR data obtained twenty years later to improve constraints on the orbital period decay rate and eccentricity of the system through pulse timing analysis. In addition, we also used long-term monitoring by Swift/BAT to independently measure orbital period evolution through eclipse timing. As a result, improved orbital ephemerides including accurate estimates of the orbital period, the period decay rate, and eccentricity of the system were obtained.

Key words. Stars: Binaries: eclipsing - Stars: Pulsars: Individual: Cen X-3 - X-ray: binaries

1. Introduction

Evolution of orbital separation and eccentricity in high mass X-ray binaries (HMXBs) is driven by several not yet fully understood mechanisms, which are particularly interesting in the context of the emerging gravitational wave astronomy (i.e. observations of merging black hole and neutron star systems). One of the most interesting objects in this regard is Centaurus X-3 (Cen X-3), the first X-ray pulsar ever discovered in 1967 during the testing of rocket-borne proportional counters (Chodil et al. 1967) and extensively studied ever since. Analysis of observations with UHURU (Giacconi et al. 1971) allowed for the detection of pulsations with a period of ~4.8 s, and a modulation of the pulsed frequency associated with motion in a binary system with an orbital period of \( P_{\text{orb}} \approx 2.1 \text{ days} \) (Schreier et al. 1972). The latter conclusion was confirmed by the discovery of regular X-ray eclipses lasting for approximately one-fourth of the orbital phase and observed each orbital cycle. The optical companion, named Krzeminski’s Star, was discovered in 1974 by Krzeminski (1974). Currently, it is understood that the binary system consists of a neutron star with a mass of \( M_N = 1.21(21)M_\odot \) and a type O(6-7) II-III companion with a mass of \( M_C = 20.5(7)M_\odot \) (Ash et al. 1999), and it is therefore classified as a HMXB.

Already the first UHURU observations suggested a complex evolution of the orbital period. A decay of the orbital period of \( P_{\text{orb}}/P_{\text{orb}} = -8.4 \times 10^{-5} \text{ yr}^{-1} \) (Schreier et al. 1973; Fabbiano & Schreier 1977), and even a short term increase in orbital period of \( P_{\text{orb}}/P_{\text{orb}} = +6(2) \times 10^{-5} \text{ yr}^{-1} \) (Fabbiano & Schreier 1977) were reported. Later measurements by Murakami et al. (1983) indicated a decay of \( P_{\text{orb}}/P_{\text{orb}} \approx -2.4 \times 10^{-6} \text{ yr}^{-1} \) over an eight year time span, which was about three times smaller than the values reported by Fabbiano & Schreier (1977), but this would be confirmed the same year by Kelley et al. (1983) reporting a steady decay of \( P_{\text{orb}}/P_{\text{orb}} = -1.78(8) \times 10^{-6} \text{ yr}^{-1} \) and was further improved by Nagase et al. (1992) to \( P_{\text{orb}}/P_{\text{orb}} = -1.734(4) \times 10^{-6} \text{ yr}^{-1} \). The newest measurements come from Raichur & Paul (2010b), who suggested \( P_{\text{orb}}/P_{\text{orb}} = -1.799(2) \times 10^{-6} \text{ yr}^{-1} \), and Falanga et al. (2015), who constrained \( P_{\text{orb}}/P_{\text{orb}} \) to \( -1.800(1) \times 10^{-6} \text{ yr}^{-1} \) via mid-eclipse timing, and they additionally confirm the orbital period and epoch reported by Raichur & Paul (2010b).

Initially the observed orbital period decay was interpreted as a result of a possible apsidal motion with a period of ~1700d in an eccentric orbit with \( e = 0.03 \) (Thomas 1974). Apsidal motion describes the rate of change of the longitude of periastron caused by a tidal interaction between the two constituents of a binary system. This effect causes subsequent measurements of the times of periastron passage to occur in increasingly shorter (or longer) intervals and can cause the effect of an apparent decay of the orbital period. Since this effect can only be observed in systems that show a non-zero eccentricity, measurements of the apsidal motion period can therefore place limits on the eccentricity of the system and vice versa. Furthermore, measurements of the apsidal motion constant can be used to constrain the age of the binary system (see e.g. Lecar et al. 1976 or Raichur & Paul 2010a). This phenomenon of apsidal motion has been observed in a number of HMXBs such as 4U 0115+63 (Raichur & Paul 2010a), as well as 4U 1538-522 and Vela X-1 (Falanga et al. 2015). For Cen X-3, however, apsidal motion was ruled out by Sparks (1975) who searched for a possible eccentricity and was able to put an upper limit on its value of \( e = 0.002 \), which would reduce the required apsidal motion period to ~100 d.
a short period should have been easily detectable with observations available at the time, and of course in currently available data; however, it was actually never observed. The upper limits on a possible eccentricity continued to steadily improve over the years to $e = 0.0008(1)$ (Fabbiano & Schreier 1977) followed by $e = 0.0004(2)$ (Kelley et al. 1983), with the latest value determined to be $e \leq 0.0001$ by Raichur & Paul (2010b). The latter work is, to the best of our knowledge, the latest study of the orbit of the source utilising pulse timing analysis and quite robustly shows that the orbit of the system is indeed circular, and thus ruling out apsidal motion.

In addition to apsidal motion, tidal interactions and mass transfer in the system have been suggested to account for orbital period decay in Cen X-3 (Sparks 1975; Kelley et al. 1983). In particular, mass exchange between the donor and accretor and non-conservative mass transfer were considered, although Kelley et al. (1983) concluded that the later option would require an implausibly high mass-loss rate. The true origin of the orbital period decay remains, however, unclear.

Similar to the steady improvement of the orbital period decay $P_{\text{orb}}/P_{\text{orb}}$ and the eccentricity $e$ of the system, the reference values for the long-term orbital period evolution of the system (reference epoch $E_0$ and corresponding orbital period $P_{\text{orb}(0)}$) have been determined with increasing accuracy over the years by multiple authors (see e.g. Fabbiano & Schreier 1977, Kelley et al. 1983, Raichur & Paul 2010b, Falanga et al. 2015 and references therein). We note that the most recent pulse timing analysis of the orbital period decay by Raichur & Paul (2010b) is still based on relatively old data from the Rossi X-ray Timing Explorer (RXTE). On June 15, 2017, almost twenty years after the launch of RXTE, the Hard X-ray Modulation Telescope (HXMT) was launched (Zhang et al. 2020) and has observed Cen X-3 on multiple occasions. This instrument, similar to RXTE, has a large effective area and is particularly well suited for timing analysis of bright sources. Another modern instrument that started operations after RXTE, NuSTAR, has also observed Cen X-3. Here we report on joint timing analysis of the data obtained by both of these missions complemented with the archival RXTE data and eclipse timing analysis based on the monitoring of the source by Swift/Burst Alert Telescope (Swift/BAT). This allows one to expand the baseline for studying the orbital period evolution by almost 4000 orbital cycles, which lie between the most recent RXTE observation and the launch of HXMT, and this is crucial for accurate measurements of the orbital period decay rate. Updated long-term ephemerides allow us to accurately estimate the instantaneous binary epoch for all observations, and thus to reduce uncertainty in modelling the pulse arrival times within multiple individual orbital cycles observed by RXTE, NuSTAR, and Insight-HXMT. We used this opportunity to revisit several long observations of the source carried out by RXTE in order to also improve the constraints on other orbital parameters, most notably, the eccentricity, which makes our work the most comprehensive analysis of the source’s orbit to date.

The paper is organised as follows: in section 2, we describe the data used in the analysis. In section 3, we describe the data analysis, starting with an arrival time analysis of the neutron star pulses in section 3.1. This is followed by the analysis of the orbital period decay in section 3.2, and we conclude with the description of the analysis steps aimed to improve the estimate of the eccentricity of the system in section 3.3.

2. Observations

RXTE observed the source seven times between MJD 50146.619 and MJD 50994.224. The data were gathered using the proportional counter array (PCA), consisting of the five proportional counters with a total collecting area of 6500 cm$^2$ covering an energy range of 2-60 keV with a time resolution of 1 μs (Swank 1999). Of special interest are the observations from 50507.155 to 50508.716 with a total exposure time of 105.180 ks and MJD 50509.059 to MJD 50510.833 with a total exposure time of 118.219 ks, as each of those covers a significant fraction of the orbital cycle of the source, which is important for estimating the orbital elements of the system.

The RXTE PCA was extremely flexible in terms of possible readout modes in order to enable extraction and telemetry to Earth with a maximal amount of information, even for bright sources. Therefore, Cen X-3 was observed in multiple readout modes with different time and energy resolutions, and energy bands. For consistency, we used the Standard1b mode of the PCA, which integrates source counts in the full energy range (i.e. contains photons within the full RXTE energy band) with a time resolution of 0.125 s. Since the spin period of the source (4.8s) is much longer, this time resolution is sufficient for the analysis. The advantage is that this mode is available for all observations, which maximises the amount of data that can be used. We note that although the count rate above 20 keV is dominated by background photons, most of the photons are detected below this energy where the total count rate is dominated by the source, so Standard1b light curves are actually dominated by source counts in most observations. To reprocess the data and extract Standard1b source light curves, HEASOFT v6.29c was used. The light curves were corrected to the Solar System barycenter using barycen tasks and used for pulsar timing as described below.

Insight-HXMT observed the source nine times between MJD 57959.582 and MJD 58480.014. For this study, we used data gathered in the energy range of 2-25 keV obtained using the Medium Energy (ME) X-ray Telescope on board of HXMT where the signal-to-noise ratio is optimal. The ME detector consists of 1728 Si-Pin detector pixels, achieving a combined detection area of 952 cm$^2$ covering an energy range of 2-30 keV with a time resolution of 280 μs and a sensitivity of 0.5 mCrab. (Li 2007; Zhang et al. 2020). The High Energy X-ray Telescope on board HXMT would provide a larger collecting area with 5000 cm$^2$ and a significantly larger energy range of 20-250 keV. However, with the collimated field of view of up to 5x5 deg, it has both a high instrument and cosmic background levels, especially at lower fluxes, which is the reason why we opted to use the smaller ME telescope instead at the cost of lower count rates. The data were reduced using HXMTDAS v6.28 using the standard cuts to clean the data as recommended in the manual. The cleaned source events were then corrected to the Solar System barycenter and binned to obtain light curves with a time resolution of 0.125s which were then also used for pulsar timing analysis.

In addition to RXTE and HXMT data, one NuSTAR observation from MJD 57356.7582 to MJD 57357.2066 was included. The four CdZnTe-detectors of NuSTAR cover an energy range from 3-79keV with an energy resolution of 0.4keV. Data from the two detector units were extracted in the energy range from 3-25 keV (where most of source counts are collected) with a time resolution of 0.125s. Again, this data were used for pulsar timing analysis. RXTE, HXMT, and NuSTAR observations used in this work are summarised in Table 1.
Finally, we also included data taken with Swift/BAT from MJD 53416.001 to MJD 59093.763. The BAT covers an energy range of 15-150 keV and has an energy resolution of ~5 keV at 60 keV with a total detection area of 5240 cm$^2$. BAT data are not really suitable for pulsar timing analysis of Cen X-3 due to comparatively low time resolution and source count rates; however, it can be used to measure times when the source undergoes an eclipse. Although the accuracy of estimated mid-eclipse times is lower than what can be obtained from pulsar timing, the advantage is that BAT continuously monitors the source, and thus covers multiple binary epochs, allowing for accurate orbital period measurements over a long time baseline. In practice, we performed a joint fit of BAT measurements and those coming from pulsar timing to get the most out of available observations.

### 3. Data analysis

#### 3.1. Pulsar timing analysis

The pulsation frequency of a pulsar moving in a binary orbit is modulated by the Doppler effect associated with orbital motion. This modifies the observed arrival times for individual pulses which thus depend on orbital parameters and the orbital phase of the pulsar at the time of emission. To determine the orbital parameters, we followed Raichur & Paul (2010b) as a first step. That is, we assumed the orbit to be circular (eccentricity $e = 0$, argument of periapsis $\omega = 0$) to determine the initial timing solution for the pulsar and to obtain a high-quality average pulse profile template for each of the analysed observations. This was done by folding the binary-corrected light curves (using ephemerides by Raichur & Paul 2010b) with the constant period value for a given segment. This template was then correlated with the observed light curve (i.e. not corrected for effects of binary motion) to determine the arrival times for individual pulses, and ultimately orbital parameters of the system.

To estimate pulse arrival times, we started by splitting the uncorrected light curves into segments containing a certain number of pulses, and folding each segment using the local period value estimated based on the constant period value derived for the entire observation and Raichur & Paul (2010b) ephemerides (i.e. we applied reverse binary correction to estimate a local spin period value for a given segment). In particular, segments consisting of 130 pulses were averaged to generate pulse profiles. Due to the lower count rates of HXMT data, we needed to find the optimal balance between profile quality and quantity for each cycle, and we averaged as many pulses as possible. The reference epoch for each pulse profile was chosen to be the starting time of the corresponding segment. Arrival times of the pulses were then obtained by transforming templates and profiles to phase space and using $\chi^2$ fitting to determine the offset in the spin phase between the pulse profiles and the template. The final arrival times of the pulses were determined by subtracting the time delay from the reference epochs of the pulses.

Considering already available stringent limits on eccentricity, and the fact that historic binary epoch estimates are reported under the assumption of a circular orbit in the literature, as well as the fact that the largest expected benefit from including HXMT data is the accuracy of the orbital period decay rate estimate, we continued the analysis under the circular orbit assumption. This assumption is well justified for individual orbital cycles, as no evidence for eccentricity was found for any single observation, and it allows for an easier and faster determination of the other parameters, most notably, the binary epoch (i.e. mid-eclipse or periastron passage time). The goal of this analysis step was to determine binary epoch for a significant number of orbital cycles and to use those to constrain the long-term evolution of the orbital period. This information was subsequently used to revisit the orbital cycles observed more or less completely with the aim to search for a possible eccentricity under the assumption of an eccentric orbit using the constraints on the binary epoch obtained based on the analysis of the long-term orbital period evolution.

For a circular orbit, the relation between emission times ($t'_n$) and arrival times ($t_n$) of the pulses and the neutron star orbit ($f_{orb}(t'_n)$) is given by equation (1) and (2) from Raichur & Paul (2010b):

$$t'_n = t_0 + n p_0 + \frac{1}{2} n^2 p_0 p_0$$

$$t_n = t'_n + f_{orb}(t'_n)$$

**Table 1. RXTE, HXMT, and NuSTAR observations.**

<table>
<thead>
<tr>
<th>Observation time-frame (MJD)</th>
<th>Orbital cycle</th>
<th>Total exposure time (ks)</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>50146.619 to 50147.600</td>
<td>4402</td>
<td>19.314</td>
<td>RXTE</td>
</tr>
<tr>
<td>50345.592 to 50345.781</td>
<td>4497</td>
<td>6.385</td>
<td>RXTE</td>
</tr>
<tr>
<td>50470.052 to 50470.161</td>
<td>4557</td>
<td>7.392</td>
<td>RXTE</td>
</tr>
<tr>
<td>50507.155 to 50508.716</td>
<td>4575</td>
<td>105.180</td>
<td>RXTE</td>
</tr>
<tr>
<td>50509.059 to 50510.833</td>
<td>4576</td>
<td>118.568</td>
<td>RXTE</td>
</tr>
<tr>
<td>50991.351 to 50992.366</td>
<td>4807</td>
<td>11.149</td>
<td>RXTE</td>
</tr>
<tr>
<td>50993.360 to 50994.224</td>
<td>4808</td>
<td>7.755</td>
<td>RXTE</td>
</tr>
<tr>
<td>57356.758 to 57357.207</td>
<td>7857</td>
<td>26.602</td>
<td>NuSTAR</td>
</tr>
<tr>
<td>57959.582 to 57961.134</td>
<td>8146</td>
<td>44.726</td>
<td>HXMT</td>
</tr>
<tr>
<td>58101.605 to 58102.677</td>
<td>8214</td>
<td>19.770</td>
<td>HXMT</td>
</tr>
<tr>
<td>58112.007 to 58112.681</td>
<td>8219</td>
<td>10.680</td>
<td>HXMT</td>
</tr>
<tr>
<td>58123.166 to 58124.403</td>
<td>8224</td>
<td>13.110</td>
<td>HXMT</td>
</tr>
<tr>
<td>58142.114 to 58143.017</td>
<td>8234</td>
<td>12.560</td>
<td>HXMT</td>
</tr>
<tr>
<td>58153.631 to 58155.001</td>
<td>8239</td>
<td>46.891</td>
<td>HXMT</td>
</tr>
<tr>
<td>58275.084 to 58275.452</td>
<td>8289</td>
<td>5.456</td>
<td>HXMT</td>
</tr>
<tr>
<td>58296.079 to 58296.317</td>
<td>8307</td>
<td>5.510</td>
<td>HXMT</td>
</tr>
<tr>
<td>58479.181 to 58480.014</td>
<td>8395</td>
<td>21.990</td>
<td>HXMT</td>
</tr>
</tbody>
</table>


\[ f_{\text{orb}} = a_n \sin(i) \cos(l_n) \]

\[ l_n = 2\pi(t'_n - E)/P_{\text{orb}} + \frac{\pi}{2}. \]  

(2)

Here, \( n \) is the spin cycle of the neutron star with respect to the reference time \( t_0 \), and \( p_0 \) is the spin period of the neutron star. Higher-order derivatives are not necessary to describe the spin period evolution as it is already well described by using only \( p_0 \) and \( p_0 \). Furthermore, \( a_n \sin i \) is the projected semi-major axis, \( l_n \) is the mean orbital longitude at time \( t'_n \), and \( E \) is the orbital epoch \( (T_0) \) of the binary system. The main parameters related to the orbit here are the projected semi-major axis, binary epoch, and orbital period. The arrival times \( t_0 \) were obtained via the correlation of the high-quality template with the individual pulses visible in the light curve.

The arrival time delay and advance of the pulses were then used to determine the epochs of individual orbital cycles using equation (1) and (2). In practice, the epochs were determined via \( \chi^2 \) fitting of (1) and (2) with \( t_0 \) and \( p_0 \) as free parameters to the measured pulse arrival times for each individual orbital cycle. As \( t_0 \) and \( p_0 \) were only determined by the spin evolution, the only free parameter related to the orbit was the binary epoch \( E \). The projected semi-major axis \( a_n \sin i \) was fixed to the corresponding value reported by Raichur & Paul (2010b), while the orbital period \( P_{\text{orb}} \) was calculated based on the ephemerides by Raichur & Paul (2010b) and then also fixed to the locally expected value for a given cycle. A representative fit for an individual orbital cycle as observed by RXTE can be seen in Fig. 1. The binary epoch values measured, as described above, together with the historic values reported in the literature are listed in Table 2. These epochs were used to derive an updated estimate of the orbital period and its decay rate.

Fig. 1. Sample delay-advance curve of RXTE observations. The solid line represents the best fit.

### 3.2. Orbital period decay

Similar to the modelling of the arrival times of the neutron star pulses, Eq. 1 can also be applied to model the binary epoch evolution and estimate the orbital period decay rate. In this case, the epoch \( E_0 \) is given by

\[ E_0 = E_0 + nP_{\text{orb}} + \frac{1}{2}n^2P_{\text{orb}}P_{\text{orb}}. \]

(3)

Here \( E_0 \) is the reference epoch for the orbital epoch history, and \( n \) is the orbit number. The first two terms of equation (3) describe the expected trend in the case of a constant orbital period. The last term describes the correction due to the orbital decay of the system.

In order to achieve better results for \( P_{\text{orb}} \) and \( P_{\text{orb}} \), we opted to also include independently estimated binary epochs obtained from eclipse timing using the data from Swift/BAT alongside the epochs obtained in the last section, as well as the historical epochs from other authors (Table 2). The Swift/BAT light curves have a time resolution of 4888 s and are thus not suited for pulsar timing analysis. Instead, we analysed the light curves as a whole.
to calculate mid-eclipse times. The mid-eclipse times in general do not coincide perfectly with epochs determined from timing analysis since the epochs from the timing analysis correspond to $T_{00}$, the time where the mean orbital longitude is $90^\circ$. For orbits with a non-zero eccentricity, the difference between $T_{00}$ and the time of mid-eclipse is given by equation 2 in Falanga et al. (2015) as

$$T_{\text{mid}} - T_{00} = \frac{P_{\text{orb}}}{\pi} \cos \omega.$$  \hfill (4)

Based on the upper limit of the eccentricity from Raichur & Paul (2010b), we find, however, that the difference is at most $\sim 5.7 \text{ s}$ for Cen X-3, that is to say below the accuracy with which we can hope to determine individual mid-eclipse times. We assume, therefore, that those two types of epochs are to be the same going forward.

The mid-eclipse times for *Swift*/BAT data were determined as follows. We first generated a template-folded orbital light curve by using all *Swift*/BAT observations and assuming that the orbital period and period derivative are known (i.e. based on Raichur & Paul (2010b) ephemerides). The mission-long light curve was then split into segments containing at least 50 orbital cycles, and data in each segment were folded with a constant period corresponding to expected value assuming ephemerides by Raichur & Paul (2010b). The folded profiles were then matched with a template using $\chi^2$ fitting in the same way as described above for pulsar timing analysis. The reference time $t_{\text{ref},n}$ for each profile was then calculated by using $E_0$, $P_{\text{orb}}$, and $P_{\text{orb}}$ from Raichur & Paul (2010b) and equation 3. Using the difference in spin phase between the template and profile, $d\phi_n$, and $t_{\text{ref},n}$, the mid-eclipse time could then be calculated with

$$T_{\text{mid},n} = t_{\text{ref},n} + \left( P_{\text{orb},\text{Raichur}} + P_{\text{orb},\text{Raichur}} \cdot (t_{\text{ref},n} - E_{0,\text{Raichur}}) \right) \cdot d\phi_n.$$  \hfill (5)

An example of a fit can be seen in Fig. 2.

The obtained mid-eclipse times from *Swift*/BAT were combined with our results from the previous section as well as the historical epochs (Table 2). The observed-minus-calculated eclipse times as function of the orbit number can be seen in Fig. 3. The calculated eclipse times were calculated based on the ephemerides reported by Raichur & Paul (2010b) assuming no orbital decay. This curve was used to determine updated values of $P_{\text{orb}}$, $P_{\text{orb}}$, and $E_0$. To account for possible systematics, we utilised the Bayesian-nested Monte-Carlo sampling code BXA (Buchner 2016, 2019; Buchner et al. 2014) to obtain the final results for $P_{\text{orb}}$, $P_{\text{orb}}$, and $E_0$. Flat priors within a reasonable range (exceeding the estimated uncertainty of respective parameter values by a factor of ten) were used for each of the parameters. The results are summarised in Table 3, together with the values obtained by Raichur & Paul (2010b).

![Fig. 2. Example of a *Swift*/BAT light curve. The solid line represents the best fit with the template.](image)

![Fig. 3. Observed-minus-calculated eclipse times including *Swift*/BAT data. The solid line represents our best fit to a constant orbital decay.](image)

### Table 3. Results of the nested Monte-Carlo sampling and corresponding values from Raichur & Paul (2010b).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$ (MJD)</td>
<td>40958.350335(26)</td>
</tr>
<tr>
<td>$E_{0,\text{Raichur}}$ (MJD)</td>
<td>40958.3502(6)</td>
</tr>
<tr>
<td>$P_{\text{orb}}$ (d)</td>
<td>2.087139842(18)</td>
</tr>
<tr>
<td>$P_{\text{orb}}$ (d)</td>
<td>2.08713936(7)</td>
</tr>
<tr>
<td>$P_{\text{orb}}$ (dd$^{-1}$)</td>
<td>1.03788(27) · 10$^{-8}$</td>
</tr>
<tr>
<td>$P_{\text{orb}}$ (yr$^{-1}$)</td>
<td>1.81632(47) · 10$^{-6}$</td>
</tr>
<tr>
<td>$P_{\text{orb},\text{Raichur}}$ (yr$^{-1}$)</td>
<td>1.799(2) · 10$^{-6}$</td>
</tr>
</tbody>
</table>

### 3.3. Updated eccentricity limits

In order further push down the upper limit on the orbital eccentricity, we also performed a joint fit using the full binary epoch history, the *Swift*/BAT mid-eclipse times, and pulse arrival times obtained from observations of three orbital cycles most densely covered by observations. In particular, it is important that the observations of the selected cycles cover most of the orbital phases with a large number of uniformly distributed measured pulse arrival times. Following these criteria, we chose orbital cycles 4575, 4576, and 8146 for our analysis. Common parameters $(\alpha, \sin i, e, \omega)$ between the cycles were linked to the corresponding parameter of the observation with the highest coverage of orbital phase, which in our case corresponds to cycle 4576. The $T_{00}$ and orbital periods of the cycles were linked to the global orbital epoch history so that their estimated value for each individual orbital cycle uses all the available data. Free parameters for
each individual orbital cycle were only the reference time for the
spin parameters, that is \( t_0 \) and the spin period \( p_0 \) (we emphasise
that all orbital parameters were also free to vary, and just linked
between all cycles). A \( \chi^2 \) fit of this joint model was first carried
out to obtain 3\( \sigma \) confidence bounds for model parameters, which
were then used to define flat priors for the nested sampling. This
procedure effectively allows one to exploit prior information on
\( T_0 \) for a particular orbital cycle given by the joint fit to long-
term \( T_0 \) evolution, and thus potentially decrease uncertainties for
other orbital elements (including eccentricity).

We note that the \( \Delta \chi^2 \) of some of the first 18 data points de-
termined by Fabbiano & Schreier (1977) show a large deviation
from the expected trend, which is consistent with results from
other papers on the source (see e.g. Fig. 2 in Kelley et al. 1983).
Since we cannot repeat the analysis for those orbital cycles as the
data for those observations are no longer readily accessible, we
attempted the following two approaches to assess the impact of
these outlier points on the accuracy of our estimate. For the first
approach we omitted the problematic data points, re-normalised
the epoch history, and repeated the fit. For the next approach
we increased the systematic of the epoch fit until we obtained a
reduced \( \chi^2 \) of \( \chi^2_{red} \approx 1.1 \). The results obtained by those three ap-
proaches to a joined fit are summarised in Table 4.

The results obtained from the epoch fit (Table 3) and from
the initial joined fit of epoch history and individual cycles (Ta-
ble 4) are consistent with each other considering uncertainties.
However, results obtained by re-normalising the epoch history
and increasing the systematic error (Table 4) do not completely
agree with each other, and also show some deviation from the
values reported in the literature. Indeed, with a di-

The period derivatives determined through both of these ap-
proaches are consistent with one another within the determined
uncertainties, but inconsistent with the period derivatives deter-
mined through the other fits presented earlier.

Furthermore, the magnitudes of the orbital period, period
derivative, and the eccentricity that were obtained by including
an additional systematic uncertainty are larger than in the case
of re-normalising the epoch history. It may be that the faster period
decay and larger eccentricity are compensated for by a lower ini-
tial orbital period, which would then also explain the discrepancy
between the orbital periods determined by the two approaches.
Considering that the results for the eccentricity of the system ob-
tained with the two approaches outlined above are also different,
we cannot consider our results as a robust detection, but rather
as an improved upper limit on the value of eccentricity. Based
on our analysis, we therefore conclude that the eccentricity of
the binary system is formally constrained between \( e = 0.00006 \)
and \( e = 0.000266 \), and conservatively adopt the latter value as a
conservative upper limit on its value.

4. Discussion and conclusions

Cen X-3 is one of the few X-ray binaries where orbital decay
is measured robustly. Measurements of the orbital period decay
can be used to place limits on the mass transfer or mass-loss rate
of the system (Deeter et al. 1981), and they are increasingly rel-
vent in the context of the emerging field of gravitational-wave
astronomy. The origin of the observed orbital decay rate in Cen
X-3 can only be unambiguously identified if both the orbital pe-
riod decay rate and eccentricity of the system are sufficiently
well constrained. In this paper we revisit this well-studied sys-
tem, combining for the first time an extensive data set accumu-
lated over the years with RXTE, HXMT, NuSTAR, and Swift/BAT
observatories with the aim to accurately determine the values
for the orbital period \( P_{orb} \) and the period decay \( \dot{P}_{orb} \). We esti-
bate \( P_{orb} = 2.087139842(18) \) d and a corresponding decay of
\( \dot{P}_{orb} = -1.03788(27) \cdot 10^{-8} \text{dd}^{-1} \), which is the most accu-
rate estimate of those parameters to date. Furthermore, using a a
joint model consisting of the full binary epoch history and the pulse
arrival times of several orbital cycles with significant coverage
of the orbital phase, we were able to constrain the eccentricity of
the system to \( 0.00006 \leq e \leq 0.000266 \). This eccentricity can be
treated either as a tentative detection or, more conservatively,
as an upper limit of the eccentricity in the system. With these
newly obtained eccentricity limits, the period of a possible ap-
sidal motion of the system can be determined. Using eq. 10 in
Thomas (1974) with an eccentricity of \( e = 0.00006 \), the apsidal
motion period results in \( P_{aps} \approx 3.5d \). Using the upper limit of
\( e = 0.000266 \) instead, one obtains an apsidal motion period of
\( P_{aps} \approx 15d \). We therefore conclude that apsidal motion cannot be
the cause for the observed apparent period decay of the system
and the observed period decay has to be explained through other
means. Assuming the change in orbital period is caused by con-
servative mass transfer with the neutron star accreting all matter
lost by the companion, the rate of change of the orbital period is
given by the following (van den Heuvel & de Loore 1973):

\[
P_{orb}/P_{orb} = 3 \frac{(M_C - M_N)}{M_C M_N} = r
\]

With an orbital period of \( P_{orb} = 2.087139842d \), a rate of
change of \( \dot{P}_{orb} = -1.037680 \cdot 10^{-8} \text{dd}^{-1} \), a neutron star mass of
\( M_N = 1.21M_\odot \), and a companion mass of \( M_C = 20.5M_\odot \)
(Ash et al. 1999), one therefore obtains roughly \( P_C = 7.784 \cdot
10^{-4} \text{M}_\odot \text{yr}^{-1} \), which is slightly above the theoretical mass loss
of \( M_C = 5.3 \cdot 10^{-4} \text{M}_\odot \text{yr}^{-1} \) derived by Falanga et al. (2015) and
considerably below the theoretical limit of \( M_C = 3 \cdot 10^{-6} \text{M}_\odot \text{yr}^{-1} \)
obtained by Wojdowski et al. (2001). If one instead considers
non-conservative mass transfer, where the neutron star only ac-
crates a fraction of the ejected matter, then following van den
Heuvel & de Loore (1973),

\[
P_{orb}/P_{orb} = (3f M_C/M_N + 1 + 3(1-f) M_N/M_C) \cdot M_C/M_C + M_N = 3M_C/M_C
\]

where \( f \) is the fraction of accreted matter. Therefore, assuming
the maximum theoretical mass loss of \( M_C = 3 \cdot 10^{-6} \text{M}_\odot \text{yr}^{-1} \)
derived by Wojdowski et al. (2001), we can estimate the fraction of
mass accreted by the neutron star as \( f = 0.3 \), meaning 70% of
the mass lost by the companion leaves the system.

This is in fact in line with the hypothesis that the mass loss
and transfer in the system occur predominantly via strong stel-
lar wind. The true cause of the observed decay is most likely
a combination of multiple mechanisms and would require more
accurate estimates of the mass-loss rate by the optical compan-
ion, and the accurate values of the orbital period, orbital period
decay, and eccentricity reported in this paper should enable fu-
ture investigations of the source to gain a deeper understanding
of the mechanisms at play.

Acknowledgements. This work made use of the data from the HXMT
mission, a project funded by China National Space Administration (CNSA) and the Chi-
nese Academy of Sciences (CAS). This work has also made use of data and/or
software provided by the High Energy Astrophysics Science Archive Research
Center (HEASARC), which is a service of the Astrophysics Science Division
at NASA/GSFC. We acknowledge the use of public data from the Swift data
archive.
Table 4. Result of the three attempts at a joined analysis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Joined analysis</th>
<th>Joined analysis (omitted points)</th>
<th>Joined analysis (increased systematic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$ (MJD)</td>
<td>40958.350346(13)</td>
<td>42438.126620(21)</td>
<td>40958.35032(15)</td>
</tr>
<tr>
<td>$P_{\text{orb}}$ (d)</td>
<td>2.0871398293(57)</td>
<td>2.087124806(15)</td>
<td>2.087140099(70)</td>
</tr>
<tr>
<td>$P_{\text{orb}}$ (d/d)</td>
<td>$-1.037680(89) \cdot 10^{-8}$</td>
<td>$-1.04205(23) \cdot 10^{-8}$</td>
<td>$-1.0422(12) \cdot 10^{-8}$</td>
</tr>
<tr>
<td>$a_t \sin i$ (lt-sec)</td>
<td>39.65260(52)</td>
<td>39.65370(97)</td>
<td>39.65447(70)</td>
</tr>
<tr>
<td>$\omega$ (deg)</td>
<td>345(24)</td>
<td>209(27)</td>
<td>190(10)</td>
</tr>
<tr>
<td>$e$</td>
<td>0.000245(21)</td>
<td>0.000101(41)</td>
<td>0.0001742(38)</td>
</tr>
</tbody>
</table>

References

Buchner, J. 2016, Statistics and Computing, 26, 383
Buchner, J. 2019, PASP, 131, 108005
Li, T.-P. 2007, Nuclear Physics B Proceedings Supplements, 166, 131
Schreier, E., Giacconi, R., Gursky, H., et al. 1973, IAU Circ., 2524, 1
Zhang, S.-N., Li, T., Lu, F., et al. 2020, Science China Physics, Mechanics, and Astronomy, 63, 249502