

Revised ephemeris and orbital period derivative of the supersoft X-ray source CAL 87 based on 34 yr of observations

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ABSTRACT

In this study, we present an analysis of over 34 yr of observational data from CAL 87, an eclipsing supersoft X-ray source. The primary aim of our study, which combines previously analysed measurements as well as unexplored publicly available data sets, is to examine the orbital period evolution of CAL 87. After meticulously and consistently determining the eclipse timings, we constructed an O – C (observed minus calculated) diagram using a total of 38 data points. Our results provide confirmation of a positive derivative in the system’s orbital period, with a determined value of $\dot{P} = +8.18 \pm 1.46 \times 10^{-11} \text{ s s}^{-1}$. We observe a noticeable jitter in the eclipse timings and additionally identify a systematic delay in the X-ray eclipses compared to those observed in longer wavelengths. We discuss the interplay of the pertinent factors that could contribute to a positive period derivative and the inherent variability in the eclipses.

Key words: stars: individual: CAL 87 – white dwarfs – X-rays: binaries.

1 INTRODUCTION

Supersoft X-ray sources (SSSs) are characterized by their very soft emission in X-rays (below $\sim 1 \text{ keV}$), blackbody-like spectra of effective temperatures $kT \sim 20\text{--}100 \text{ eV}$ and high bolometric luminosities of $\sim 10^{36\text{--}38} \text{ erg s}^{-1}$ (e.g. Kahabka & van den Heuvel 1997). van den Heuvel et al. (1992) showed that the soft X-ray emission observed in SSSs originates from stable hydrogen burning on the surface of a massive ($\gtrsim 1 M_{\odot}$) white dwarf (WD) which accretes at very high rates ($\sim 10^{-7} M_{\odot} \text{ yr}^{-1}$) from its companion. For this high-mass accretion to be sustained, argued van den Heuvel et al. (1992), the companion star (with mass M_2) of the binary system should be even more massive than the WD (M_1), that is, a mass ratio $M_2/M_1 = q > 1$, which would lead to dynamically unstable mass transfer via Roche lobe overflow (RLOF). An alternative scenario was proposed by van Teeseling & King (1998), in which wind-driven mass transfer (WDMT) could also account for the high accretion rates in systems where the companion star is less massive, that is, $q < 1$. This would also explain SSSs with orbital periods shorter than $\sim 6 \text{ h}$.

CAL 87 is a well-known SSS located in the Large Magellanic Cloud (LMC). It was, along with CAL 83, the first supersoft object detected (Long, Helfand & Grabelsky 1981), considered thus to be a prototype of the class. By placing observational parameters obtained from X-ray spectral analyses of CAL 87 in a luminosity–temperature

diagram, computed for surface hydrogen-burning WDs, Starrfield et al. (2004) inferred that the WD in the system might be as massive as $1.35 M_{\odot}$. Optical spectroscopic data revealed Balmer absorption lines whose radial velocities suggest that – for a $1.3\text{--}1.4 M_{\odot}$ compact object – the donor should have no more than $0.4 M_{\odot}$ (Hutchings et al. 1998). An orbital evolutionary analysis performed by Oliveira & Steiner (2007) pointed to a $0.34 M_{\odot}$ donor, corroborating the low-mass nature of the companion star in CAL 87. These values lead to a mass ratio of $q \approx 0.25\text{--}0.3$.

Light-curve analyses have shown that CAL 87 exhibits partial eclipses in optical (Callanan et al. 1989; Cowley et al. 1990; Alcock et al. 1997; Oliveira & Steiner 2007), ultraviolet (UV, Hutchings et al. 1995), and X-rays (Schmidtke et al. 1993; Asai et al. 1998; Greiner et al. 2004; Ebisawa, Rauch & Takei 2010) with a period of approximately 0.44 d (10.6 h). The depths of the eclipses imply a high orbital inclination ($> 70^{\circ}$, e.g. Schandl, Meyer-Hofmeister & Meyer 1997). An increase in the system’s orbital period ($\dot{P} = +1.7 \pm 0.3 \times 10^{-10} \text{ s s}^{-1}$) was reported by Oliveira & Steiner (2007) based on an estimation from two optical minima that were approximately 9000 cycles apart. Ribeiro, Lopes de Oliveira & Borges (2014) also derived a positive value ($\dot{P} = +6 \pm 2 \times 10^{-10} \text{ s s}^{-1}$) from the X-ray eclipse phase shift (relative to longer wavelengths) present in *XMM-Newton*’s data of CAL 87. The authors of both aforementioned studies have advocated that the increasing orbital period, coupled with the low-mass ratio, favours the WDMT model; Ablimit & Li (2015) demonstrated through analytical and numerical calculations of orbital evolution that the reported dynamical parameters of CAL 87 indeed admit such a scenario.

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In this study, we compiled archival data spanning a 34-yr time baseline for CAL 87. The primary goal of this compilation was the construction of an O – C (observed minus calculated) diagram, which serves as the basis for a comprehensive analysis of orbital period variations and other related phenomena. While certain data sets have been previously analysed, our approach includes several previously unexamined light curves, rendering them novel in the context of this investigation.

2 DATA COLLECTION AND DETERMINATION OF ECLIPSE TIMINGS

The times of minimum were essentially obtained through two different approaches: taken from published ephemerides or determined by us after analysing publicly available data. In the latter case, the data points used to build the light curves are sourced from either previously published measurements or archival data publicly available in survey/project catalogues.

Eclipse timings seized directly from published works are those from the Cerro Tololo Inter-American Observatory (CTIO; one minimum – *B*, *V*, and *R* bands altogether; Cowley et al. 1990), the European Southern Observatory and the South African Astronomical Observatory (ESO and SAAO; one minimum – *B* and *V* bands altogether; Callanan et al. 1989), and the Southern Astrophysical Research Telescope (SOAR; *V* band; Oliveira & Steiner 2007). They are marked with an asterisk in Table 1. The *Hubble Space Telescope* (*HST*, UV band) and a second CTIO (*V* band) minima were determined based on measurements presented in table 1 of Hutchings et al. (1995) and table 2 of Hutchings et al. (1998), respectively.

All other data sets were collected from public catalogues. These are the light curves from the Massive Compact Halo Objects project¹ (MACHO; two minima – a ‘blue’ and a ‘red’ band), the Optical Gravitational Lensing Experiment² (OGLE; two minima, a *V* and a *I* band), the Visual and Infrared Telescope for Astronomy (VISTA) Magellanic Clouds survey³ (VMC; one minimum – *Y*, *J*, *K_S* bands altogether), and the Transiting Exoplanet Survey Satellite⁴ (*TESS*; 28 minima, in a wide *I* band). Except for *TESS* (which will be explained shortly), the aforementioned data were straightforwardly retrieved as magnitudes versus time. Data from MACHO had already been analysed by Alcock et al. (1997), who reported the ephemeris $T_{0,\text{Alcock}} = \text{MJD } 50111.0144(3) + 0.44267714(6)$, most commonly cited up to the present day.

The *TESS* light curves were produced from aperture photometry on the Full Frame Images (FFIs) of 31 sectors. Each sector spans about 26 d of observations, at a cadence of 30, 10, or 3 min. Three of the sectors were discarded due to the target being too close to the edge of the detector. The aperture photometry was performed with LIGHTKURVE (Lightkurve Collaboration 2018), an open source PYTHON package written for *TESS* and *Kepler* data analysis. From each FFI we made a 11×11 pixels cutout centred on the target. The light curves were obtained from those cutouts by measuring the total flux in a 2×2 pixel mask that includes the target, subtracted of the sky average flux obtained from a background mask. The resulting data are given in flux ($e^- s^{-1}$) versus Barycentric *TESS* Julian Date

¹<http://cdsarc.u-strasbg.fr/viz-bin/VizieR-5?-ref=VIZ642dda8b315c&-out.add=&-source=II/247/machovar&recno=4458>

²<https://ogleb.astrouw.edu.pl/~ogle/OCVS/?OGLE-LMC-ECL-24119>

³<https://archive.eso.org/scienceportal/home?data.collection=VMC>

⁴<https://mast.stsci.edu>

Table 1. Epochs of minimum.

| Epoch of minimum (MJD) | Uncertainty in epoch (d) | Cycle [†] | Provenance | Band |
|------------------------|--------------------------|--------------------|------------|--|
| 47506.30210* | 0.0002 | –5884 | CTIO | <i>B</i> , <i>V</i> , <i>R</i> |
| 47531.09520* | 0.0030 | –5828 | ESO & SAAO | <i>B</i> , <i>V</i> |
| 48306.67950 | 0.0110 | –4076 | ROSAT | X-rays ^a |
| 49724.11870 | 0.0060 | –874 | HST | UV ^b |
| 50028.23574 | 0.0024 | –187 | CTIO | <i>V</i> |
| 50180.51280 | 0.0015 | 157 | MACHO | b ^c |
| 50182.72351 | 0.0019 | 162 | MACHO | r ^d |
| 52135.38977 | 0.0079 | 4573 | Chandra | X-rays |
| 52748.49518 | 0.0014 | 5958 | XMM–Newton | X-rays |
| 53680.32440* | 0.0003 | 8063 | SOAR | <i>V</i> |
| 56001.28307 | 0.0021 | 13306 | OGLE | <i>I</i> |
| 56022.53521 | 0.0011 | 13354 | OGLE | <i>V</i> |
| 56632.97981 | 0.0060 | 14733 | VMC | <i>Y</i> , <i>J</i> , <i>K_S</i> |
| 58338.62551 | 0.0039 | 18586 | TESS | Wide <i>I</i> ^e |
| 58367.39827 | 0.0019 | 18651 | TESS | Wide <i>I</i> |
| 58423.17168 | 0.0040 | 18777 | TESS | Wide <i>I</i> |
| 58450.17719 | 0.0051 | 18838 | TESS | Wide <i>I</i> |
| 58478.51156 | 0.0053 | 18902 | TESS | Wide <i>I</i> |
| 58503.30069 | 0.0042 | 18958 | TESS | Wide <i>I</i> |
| 58529.42007 | 0.0056 | 19017 | TESS | Wide <i>I</i> |
| 58555.53251 | 0.0029 | 19076 | TESS | Wide <i>I</i> |
| 58582.09385 | 0.0025 | 19136 | TESS | Wide <i>I</i> |
| 58609.99029 | 0.0042 | 19199 | TESS | Wide <i>I</i> |
| 58638.76056 | 0.0042 | 19264 | TESS | Wide <i>I</i> |
| 59047.79394 | 0.0053 | 20188 | TESS | Wide <i>I</i> |
| 59073.91511 | 0.0046 | 20247 | TESS | Wide <i>I</i> |
| 59100.91171 | 0.0046 | 20308 | TESS | Wide <i>I</i> |
| 59156.68956 | 0.0036 | 20434 | TESS | Wide <i>I</i> |
| 59186.79344 | 0.0040 | 20502 | TESS | Wide <i>I</i> |
| 59241.25008 | 0.0034 | 20625 | TESS | Wide <i>I</i> |
| 59267.37093 | 0.0024 | 20684 | TESS | Wide <i>I</i> |
| 59293.48852 | 0.0033 | 20743 | TESS | Wide <i>I</i> |
| 59319.60339 | 0.0043 | 20802 | TESS | Wide <i>I</i> |
| 59346.60482 | 0.0045 | 20863 | TESS | Wide <i>I</i> |
| 59375.37238 | 0.0020 | 20928 | TESS | Wide <i>I</i> |
| 59975.20202 | 0.0019 | 22283 | TESS | Wide <i>I</i> |
| 60000.88383 | 0.0043 | 22341 | TESS | Wide <i>I</i> |
| 60026.99755 | 0.0037 | 22400 | TESS | Wide <i>I</i> |
| 60053.99849 | 0.0016 | 22461 | TESS | Wide <i>I</i> |
| 60081.89137 | 0.0054 | 22524 | TESS | Wide <i>I</i> |
| 60110.22337 | 0.0056 | 22588 | TESS | Wide <i>I</i> |

Notes. * Epochs taken from the literature.

[†] Based on the cycle counting of Alcock et al. (1997).

^a 0.2–1.0 keV.

^b 1350–2200 Å.

^c $\sim V$.

^d $\sim R+I$.

^e ~ 6000 – $10\,000$ Å.

(BTJD), defined as $\text{BTJD} = \text{BJD} - 2,457,000$, where BJD is the Barycentric Julian Date.

Some of the data have not been previously mentioned in the literature; this applies to the measurements of CAL 87 from OGLE, VMC, and *TESS*. Their folded light curves are displayed in Fig. 1. For *TESS*, from which we use data from multiple sectors and thus obtain multiple eclipsing times, we present the light curve from one sector.

While our primary focus was not on incorporating X-ray eclipses into the period evolution analysis, we retrieved historical X-ray light curves to examine their correlation with those at longer wavelengths. X-ray data reduction and light-curves production were accomplished

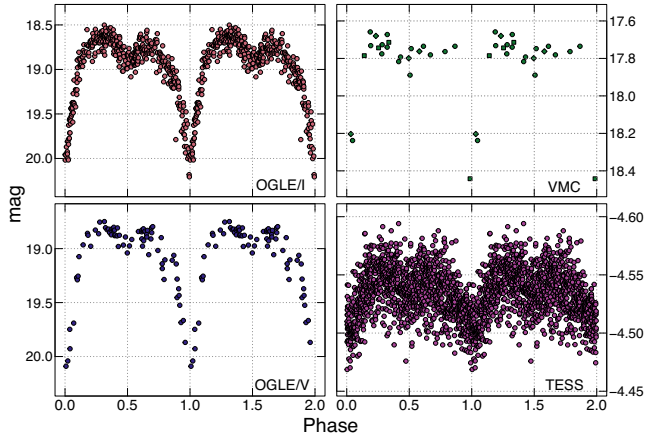


Figure 1. Folded light curves of CAL 87 from archival data not previously analysed. The light curves are folded with the linear ephemeris presented in equation (1) (Section 3). Two cycles are shown for clarity. OGLE data (left panels): vertical axes show the actual magnitude measured in bands *I* (upper) and *V* (bottom). VMC data (upper right panel): circles, squares, and diamonds refer, respectively, to measurements in bands K_S , *Y*, and *J*. Vertical axis shows magnitude for K_S ; the *Y* and *J* data points were shifted to match the K_S level out of eclipse. *TESS* (sector 11) data (bottom right panel): straightforwardly converted from flux to magnitude ($-2.5 \log f$), that is, the actual units for the vertical axis are Δmag . The relatively small amplitude and large scatter are due to light dilution caused by the presence of numerous other sources within the *TESS* 2×2 pixels extraction aperture where CAL 87 is found.

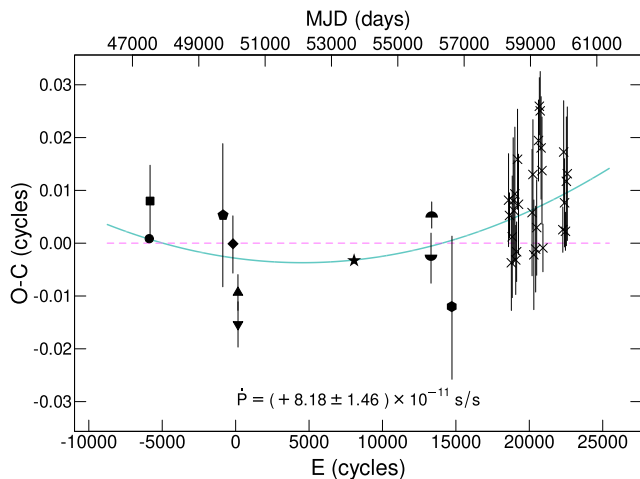


Figure 2. O – C diagram computed for the data presented in Table 1 (except for the X-ray data). Both computations incorporated the uncertainties of the measurements as weighting factors. Vertical error bars are shown for all data points, although in some cases the bars are smaller than the symbols representing them. Circle: epoch taken from Cowley et al. (1990); square: epoch taken from Callanan et al. (1989); pentagon: *HST*/UV data, taken from Hutchings et al. (1995); diamond: CTIO data, taken from Hutchings et al. (1998); up-pointing triangle: MACHO/b; down-pointing triangle: MACHO/r; star: epoch taken from Oliveira & Steiner (2007); top half circle: OGLE/*I*; bottom half circle: OGLE/*V*; hexagon: VMC; and crosses: *TESS*. Dashed and solid lines are linear and quadratic fits, respectively. The fits keep the cycle counting of Alcock et al. (1997).

following each mission’s standard procedures: XSELECT tasks from the FTOOLS package (HEASOFT, v. 6.32) for PSPC (Position Sensitive Proportional Counter) data from *ROSAT*, the *Chandra* Interactive Analysis of Observations (CIAO, v. 4.15.0) for ACIS-S data from

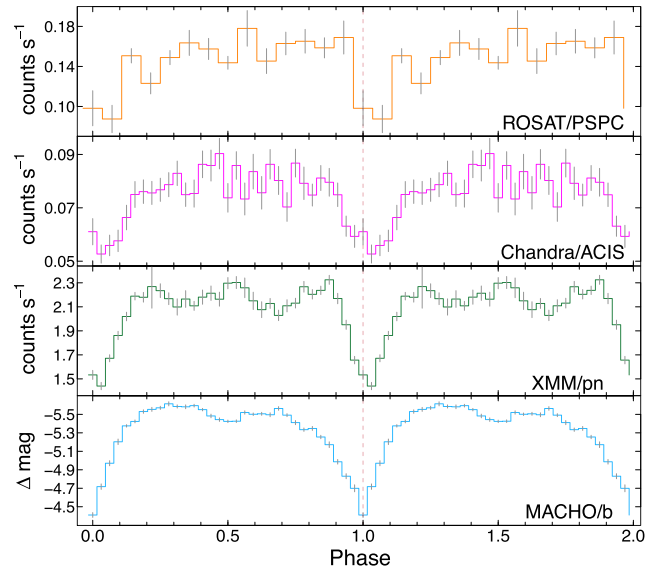


Figure 3. Phase diagrams of CAL 87 to evince the displacement of the X-ray (0.2–1 keV; first, second and third panels) eclipse minimum time relative to longer wavelengths (optical; bottom panel). Light curves were folded according to the linear ephemeris presented in equation (1). Two cycles are shown for clarity. Binning consists of 32 bins per phase, except for *ROSAT* (first panel), in which only 14 bins per phase were used due to the uneven distribution of data throughout an orbital cycle.

Chandra, and the *XMM–Newton* Science Analysis System (SAS, v. 20.0.0) for EPIC-pn data from *XMM–Newton*. All light curves were extracted for the energy band 0.2–1 keV. *ROSAT*’s observation spanned over 60 h, although there were numerous gaps. *Chandra* and *XMM–Newton* observations of CAL 87 were continuous over more than one orbital cycle, encompassing 3 and 2 full eclipses, respectively. The phase diagrams for the X-ray data are presented in Fig. 3 later in this paper.

To determine a composite time of minimum for each dataset, we started with a provisional epoch close to the middle of the data set. The precise time of minimum was extracted with respect to this epoch using a spline fit with the aid of the `loess()` function in the R statistical package. To estimate the uncertainty in the derived time of minimum, a bootstrap technique was employed. This technique involves resampling each flux value around its nominal value based on the corresponding 1σ error bar. The median of the absolute deviations from one thousand realizations of this procedure was used to calculate the standard deviation of the timing. In Table 1, we present the final epochs of minimum and their uncertainties, keeping the cycle number relative to the ephemeris of Alcock et al. (1997), and general information regarding the observations. For brevity, all the time stamps are expressed in MJD (Modified Julian Date), that is, HJD or BJD – 2,400,000.5.

3 THE O – C DIAGRAM FOR CAL 87

The best-fitting weighted linear ephemeris ($T_{\min} = T_0 + P_0 E$), calculated when considering all epochs of minimum listed in Table 1 – except for the X-ray data – is

$$T_{\min} = \text{MJD } 50111.01655(28) \pm 0.442677572(33) E, \quad (1)$$

where E is the number of elapsed cycles since T_0 .

To investigate a potential orbital period derivative (\dot{P}), we incorporated a quadratic term in the ephemeris using the well-known Taylor expansion (i.e. $T_{\min} = T_0 + P_0 E + \frac{1}{2} P_0 \dot{P} E^2$, keeping the same notation). The resulting weighted parabolic fit yields

$$T_{\min} = \text{MJD } 50111.01530(13) + 0.442677407(34) E + 1.81(32) \times 10^{-11} E^2, \quad (2)$$

which translates to a time derivative of $\dot{P} = +8.18 \pm 1.46 \times 10^{-11} \text{ s s}^{-1}$. Employing the reduced chi-squared ($\chi_{\text{red}}^2 = \chi^2/\nu$, where χ^2 denotes the standard chi-square statistic and ν represents the degrees of freedom) as a measure of goodness of fit, we obtain $\chi_{\text{red}}^2 = \frac{49.49}{36} = 1.37$ and $\chi_{\text{red}}^2 = \frac{37.46}{35} = 1.07$ for the linear and quadratic fits, respectively. Both an F -test and a χ^2 difference test show that there is less than a 0.1 per cent probability that the null hypothesis (i.e. the linear model) is the best choice. Moreover, upon computing the Akaike (1978) Weight, which expresses the likelihood of a model best representing the data among a set of models, we find that the parabolic model is approximately 99 per cent more plausible in describing the evolution of CAL 87's epochs of minimum. The data, along with the linear and quadratic fits, are presented in Fig. 2 in the form of an O – C diagram.

We have excluded X-ray eclipsing times from the O – C calculation based on a previous hint that they may not precisely coincide with the optical eclipse. Ebisawa et al. (2010), in their analysis of the *XMM-Newton* observation of CAL 87 (which we also employ here), reported a $\sim 0.03 \phi$ delay compared to the ephemeris of Alcock et al. (1997). Indeed, the weighted average of the residuals for the three X-ray minima analysed here (see Table 1), relative to those predicted by equation (2), is 0.02 ± 0.01 . For clarity and visualization of such a delay, we present in Fig. 3 the phase diagram of the three X-ray (0.2–1 keV) light curves (*ROSAT*/PSPC, *Chandra*/ACIS, and *XMM-Newton*/pn), as well as that of MACHO/b, that is, in the optical band. They are folded according to the linear ephemeris of equation (1). The observation gaps in *ROSAT*'s data prevented sufficient coverage of all orbital phases; as a result, its folded light curve has a coarser binning (14 bins per phase) compared to the other three, which have 32 bins per phase. We have not attempted to derive an ephemeris for the X-ray eclipses alone due to (i) the small number of data points to fit a parabola, (ii) the minima's relatively large uncertainties, and (iii) their irregular distribution along the time baseline (*XMM-Newton* and *Chandra* timings too close and *ROSAT* timing about 10 000 cycles apart).

At last, to facilitate assessment of the differences in shape of the light curves of CAL 87 in X-rays and optical, we present again the phase diagrams of *XMM-Newton* and MACHO superimposed in Fig. 4. For a clearer comparison, MACHO magnitudes have been converted to flux by simply calculating $10^{(-0.4 \times \text{mag})}$, and the flux values of both have then been rescaled to ensure the same range between minimum and maximum. Also, the X-ray minimum has been adjusted to align in phase with the optical minimum.

4 DISCUSSION AND CONCLUSIONS

Conspicuous differences between the eclipse profiles in the optical/infrared (IR) and X-rays are found. The eclipse seems to display opposite asymmetries: its ingress is prolonged in the optical/IR and steeper in X-rays, whereas the egress is slower than the ingress in X-rays (Fig. 4). In addition to the profiles, the X-ray minimum is observed to be delayed compared to the optical (Fig. 3). These differences indicate that the corresponding sources are not equally distributed around the WD. For instance, if the major contribution

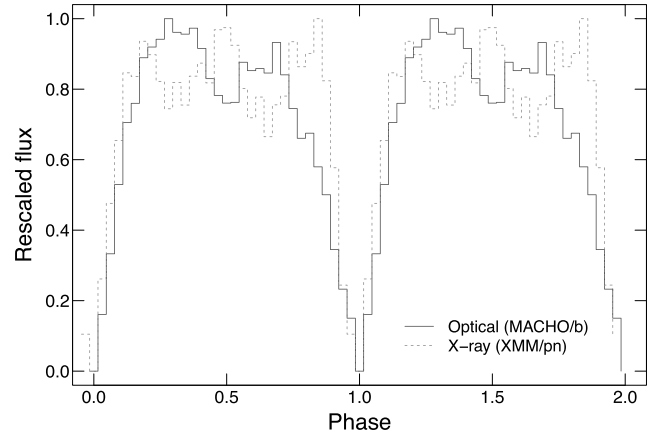


Figure 4. Optical (solid line) and X-ray (dashed line) phase diagrams of CAL 87, superimposed to highlight shape differences. For comparison purposes, the optical magnitudes have been converted to flux, and the flux values of both light curves have been rescaled to share the same minimum and maximum values. Additionally, the X-ray minimum, originally delayed with respect to the optical (Fig. 3), has been adjusted to match the optical minimum.

to X-rays is associated with the disc–WD boundary layer then the true geometrical conjunction is around phase 0.02. If that is the case, such a change in absolute phasing should be taken into account when deriving binary dynamical solutions from eclipse-phased radial velocity measurements. On the other hand, the eclipse timings used in the optical O – C diagram (Table 1) have well-defined uncertainties. When phased, they exhibit a notable phase jitter (Fig. 2), suggesting an inherently variable phase of minimum light, by a few degrees. One may conjecture that variable asymmetries in the disc's optical emission or in an optically thick wind might explain these small shifts in minimum phase (e.g. Meyer-Hofmeister, Schandl & Meyer 1997). An anticorrelation between the optical and X-ray flux around phase 0.5 becomes apparent upon comparing the phase-folded curves in Fig. 3, specially from MACHO and *XMM-Newton* data (e.g. Pearson correlation coefficient of -0.59 within phases 0.35 and 0.65; see also Fig. 4), which could be related to the contrasting eclipse asymmetry. Such anticorrelation is less clear for *ROSAT* or *Chandra* light curves, perhaps due to poorer photon statistics. Additional simultaneous multiwavelength observations are required to confirm and quantify this behavior, which has also been seen in other SSSs (e.g. CAL 83, Stecchini et al. 2023).

In order to evaluate the secular binary period evolution it is important to quantify the period change using the most extensive time baseline available. Low-frequency noise in O – C diagrams of accreting systems can mislead the observer towards a spurious, yet statistically significant, \dot{P} value.

The observed long-term positive \dot{P} for this system serves as a probe to elucidate the roles of winds, angular momentum losses, and mass ratio in SSSs. Accretion onto the WD may occur via RLOF or via wind from a detached irradiated companion. In the context of non-conservative mass transfer, a well-established dynamical relation exists between \dot{P}/P , the mass-loss rate, M_1 , M_2 , the primary accretion rate, and, for long-period systems, the efficiency of magnetic braking, in the case of a circular orbit (e.g. Hilditch 2001). Radiation-driven winds are expected to emerge from both the luminous WD's photosphere and the irradiated companion. These winds carry both mass and angular momentum, with the former contributing positively to \dot{P} . Magnetic braking, even in a weak wind

from the companion star, introduces a negative contribution. The process of accretion onto the WD itself plays a major role, resulting in either a negative or positive term depending on whether the donor is more massive or less massive than the WD. Our determination of the period derivative favours the hypothesis of mass loss and/or a lighter donor relative to the accreting object. A positive \dot{P} was previously identified for CAL 87 by Oliveira & Steiner (2007), who suggested that the system is powered by the companion wind (the WDMT model) instead of RLOF. Ribeiro et al. (2014) also reported a positive period derivative, which was larger than our value, using a small number of X-ray eclipse timings.

Curiously, the SSS-like binary V Sge (Steiner & Diaz 1998), which has a comparably long orbital period, seems to exhibit a distinct mass transfer/wind regime. A decreasing orbital period has been claimed for this eclipsing system (Patterson et al. 1998; Zang et al. 2022), suggesting a RLOF, high-mass transfer rate from the donor. WX Cen, another binary system of the V Sge class (Diaz & Steiner 1995; Oliveira & Steiner 2004), also shows an orbital period with a negative time derivative (Zang, Qian & Fernández-Lajús 2023). In this case, the secondary component is likely less massive than the WD, and thus angular momentum loss driven by a magnetic wind has been proposed as the mechanism for the orbital evolution. In contrast, V617 Sgr, also known as a V Sge-type eclipsing system, exhibits a positive \dot{P} (Steiner et al. 2006; Zang et al. 2023) with the same order of magnitude as found for CAL 87. A positive \dot{P} is also observed in the long-period eclipsing SSS QR And (Zang et al. 2023), which presents an optical orbital light curve remarkably similar to that of CAL 87.

Revised dynamical constraints on stellar masses, well-defined long-term period derivatives, and limits on system mass loss are essential for a more accurate understanding of the mass transfer modes in SSSs. These fundamental quantities remain uncertain or unknown for nearly all bona fide SSSs.

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a PYTHON package for *Kepler* and *TESS* data analysis (Lightkurve Collaboration 2018).

DATA AVAILABILITY

The data underlying this article are public; the references and/or paths to access are provided in the main text.

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