

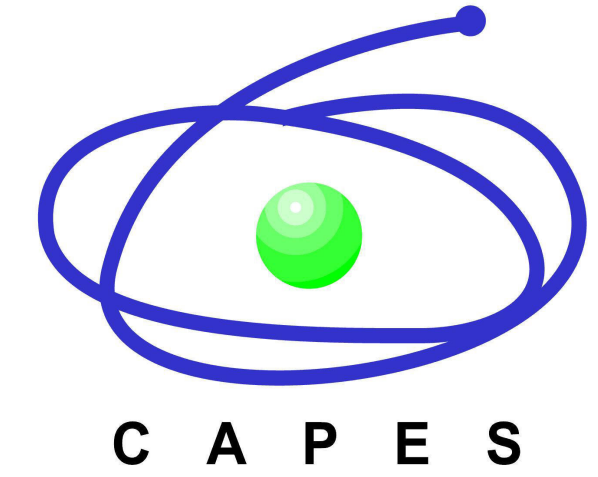


Two bodies with high-eccentricity around the cataclysmic variable QS Vir

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Abstract

QS Vir is an eclipsing cataclysmic variable with 3.618 hrs orbital period. This system has the interesting characteristics that it does not show mass transfer between the components through the L1 Lagrangian point and shows a complex orbital period variation history. Qian et al. (2010) associated the orbital period variations to the presence of a giant planet in the system plus angular momentum loss via magnetic braking. Parsons et al. (2010) obtained new eclipse timings and observed that the orbital period variations associated to a hypothetical giant planet disagree with their measurements and concluded that the decrease in orbital period is part of a cyclic variation with period ~ 16 yrs. In this work, we present 28 new eclipse timings of QS Vir and suggest that the orbital period variations can be explained by a model with two circumbinary bodies. The best fitting gives the lower limit to the masses $M_1 \sin(i) \sim 0.009 M_\odot$ and $M_2 \sin(i) \sim 0.049 M_\odot$; orbital periods $P_1 \sim 7.6$ yrs and $P_2 \sim 17.2$ yrs, and eccentricities $e_1 \sim 0.62$ and $e_2 \sim 0.9$ for the two external bodies. Under the assumption of coplanarity among the two external bodies and the inner binary, we obtain $M_1 \sim 0.0093 M_\odot$ and $M_2 \sim 0.05 M_\odot$.

1. Introduction

QS Vir is an eclipsing binary consisting of a white dwarf plus a red dwarf that has spectral type M3.5-M4 (O'Donoghue et al. 2003). It was discovered in the Edinburgh-Cape faint blue object survey (Kilkenny et al. 1997). O'Donoghue et al. (2003) using the information about the white dwarf spin suggested that QS Vir is a hibernating cataclysmic variable. With orbital period close to the period-gap of the cataclysmic variables (CVs), 3.618 hrs, and a secondary close to the transition between stars with a radiative core and completely convective stars, this CV is an interesting target for more detailed studies.

Here, we present 28 new eclipse timings of QS Vir from May to August, 2010. We gathered these to all measurements in the literature and re-analysed the orbital period variation of this system. We suggest that a plausible explanation for the orbital period variations is the presence of two bodies with high-eccentricity around the binary.

2. Observations and data reduction

The data were collected along an observational program on orbital period variations of compact binaries that is being carried out with the facilities of Laboratório Nacional de Astrofísica (LNA/MCT). Table 1 summarizes the characteristics of the data collected for QS Vir.

Table 1: Log of the photometric observations and new eclipse timings for QS Vir

| Date | N | L_{exp} (s) | Telescope | Filter | Cycle | Eclipse Timing (MJD(BTJD)) |
|--------------|------|----------------------|-----------|------------|-------|----------------------------|
| May 15, 2010 | 8500 | 2 | 1.6-m | V | 44063 | 55331.96800 \pm 0.000015 |
| | | | | | 44064 | 55332.11872 \pm 0.000015 |
| May 20, 2010 | 3000 | 2 | 1.6-m | V | 44096 | 55336.94300 \pm 0.000015 |
| May 21, 2010 | 8300 | 2 | 1.6-m | Unfiltered | 44103 | 55337.99835 \pm 0.000015 |
| | | | | | 44104 | 55338.14909 \pm 0.000015 |
| Jun 01, 2010 | 2800 | 5 | 0.6-m | Unfiltered | 44177 | 55349.15437 \pm 0.000029 |
| Jun 03, 2010 | 4000 | 4 | 0.6-m | Unfiltered | 44189 | 55350.96347 \pm 0.000023 |
| Jun 12, 2010 | 800 | 6 | 0.6-m | Unfiltered | | |
| Jun 16, 2010 | 4500 | 4 | 0.6-m | Unfiltered | 44275 | 55363.92863 \pm 0.000023 |
| | | | | | 44276 | 55364.07937 \pm 0.000023 |
| Jun 17, 2010 | 4900 | 4 | 0.6-m | Unfiltered | 44282 | 55364.98394 \pm 0.000023 |
| | | | | | 44283 | 55365.13470 \pm 0.000023 |
| Jun 18, 2010 | 4000 | 5 | 0.6-m | Unfiltered | 44289 | 55366.03922 \pm 0.000029 |
| Jun 19, 2010 | 2800 | 4 | 0.6-m | Unfiltered | 44295 | 55366.94377 \pm 0.000023 |
| | | | | | 44296 | 55367.09452 \pm 0.000023 |
| Jun 20, 2010 | 2500 | 6 | 0.6-m | Unfiltered | 44302 | 55367.99909 \pm 0.000035 |
| Jun 21, 2010 | 2000 | 5 | 0.6-m | Unfiltered | 44309 | 55369.05439 \pm 0.000039 |
| Jul 06, 2010 | 3000 | 4 | 0.6-m | Unfiltered | 44408 | 55383.97940 \pm 0.000023 |
| Jul 07, 2010 | 3350 | 4 | 0.6-m | Unfiltered | 44415 | 55385.03469 \pm 0.000023 |
| Jul 08, 2010 | 4000 | 4 | 0.6-m | Unfiltered | 44421 | 55385.93924 \pm 0.000023 |
| | | | | | 44422 | 55386.08998 \pm 0.000023 |
| Jul 10, 2010 | 3000 | 4 | 0.6-m | Unfiltered | 44434 | 55387.89908 \pm 0.000023 |
| | | | | | 44435 | 55388.04983 \pm 0.000023 |
| Jul 11, 2010 | 3500 | 4 | 0.6-m | Unfiltered | 44441 | 55388.95439 \pm 0.000023 |
| Jul 21, 2010 | 1000 | 8 | 0.3-m | Unfiltered | 44508 | 55399.05516 \pm 0.000046 |
| Jul 30, 2010 | 2000 | 4 | 0.6-m | Unfiltered | 44567 | 55407.94984 \pm 0.000023 |
| Jul 31, 2010 | 2250 | 4 | 0.6-m | Unfiltered | 44574 | 55409.00516 \pm 0.000023 |
| Aug 02, 2010 | 2000 | 4 | 0.6-m | Unfiltered | | |
| Aug 18, 2010 | 1500 | 4 | 0.6-m | Unfiltered | 44693 | 55426.94531 \pm 0.000023 |
| Aug 20, 2010 | 1500 | 4 | 0.6-m | Unfiltered | 44706 | 55428.90514 \pm 0.000023 |

The reduction of the photometric data was done with the usual IRAF `cl` tasks and consists of subtracting a master median bias image from each program image, and dividing the result by a normalized flat-field. Figure 1 shows some light curves obtained in our program.

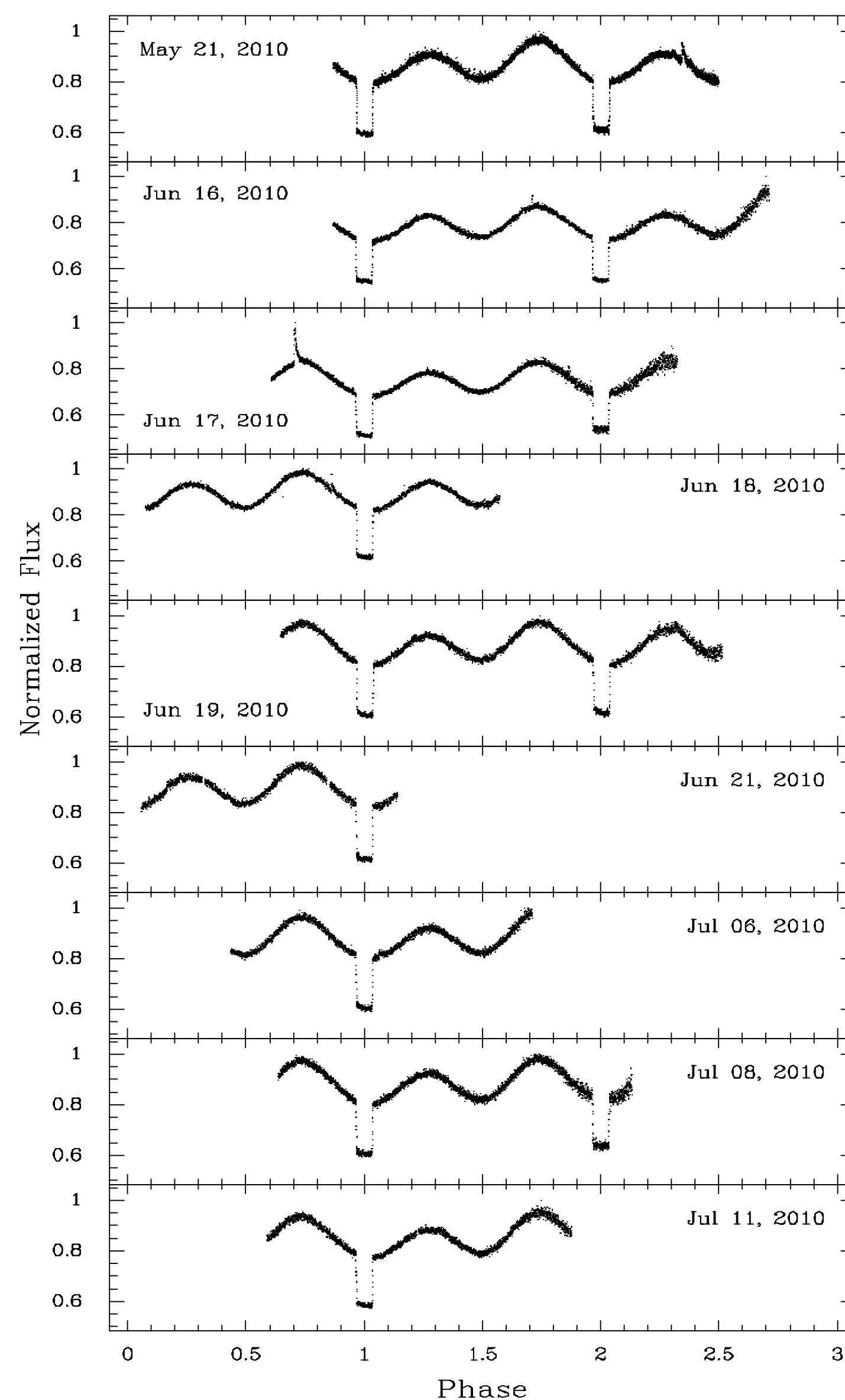


Figure 1: Unfiltered light curves of QS Vir obtained with the 1.6-m and 0.6-m telescopes at Picos dos Dias Observatory, Brazil.

3. Analysis and Results

3.1 Eclipse timings

We use the Wilson-Devinney code (Wilson & Devinney 1971) to fit the light curves of QS Vir to obtain the mid-eclipse timings. The geometrical and physical parameters, e.g., inclination, radii, temperatures and masses obtained by O'Donoghue et al. (2003) for QS Vir were adopted as initial values for the fitting procedure. In Figure 2, we show a result of this procedure for the light curve obtained on May 21, 2010. We estimated that the error of the mid-eclipse timings is of the order of seconds. Table 1 shows the mid-eclipse timings obtained by us.

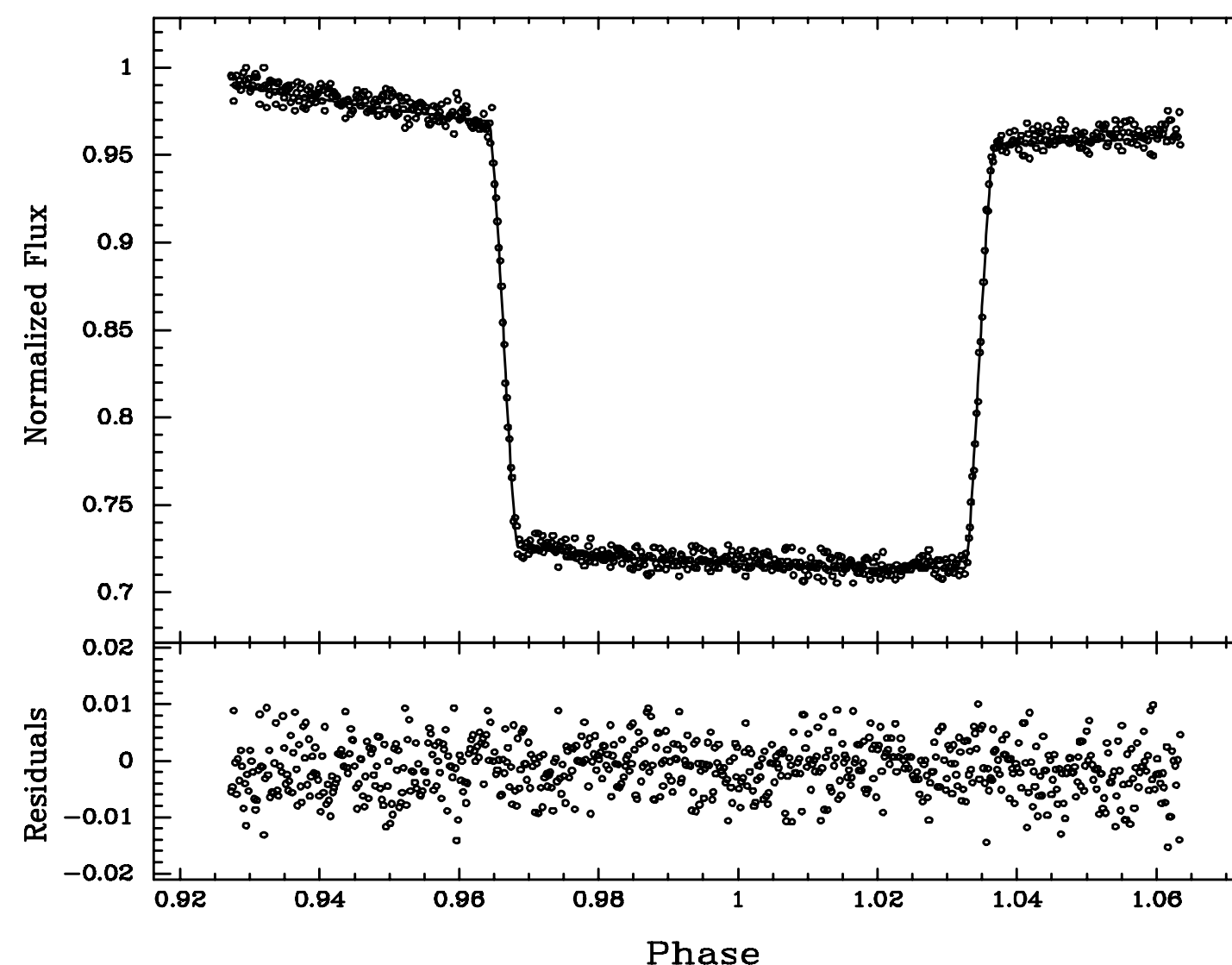


Figure 2: Upper panel: light curve and model fit to the primary eclipse of QS Vir observed on 21 May, 2010. A linear slope was added to account for the varying brightness of the secondary star. Lower panel: The residuals obtained from the fitting procedure.

3.2 Orbital period variation

Initially we examined if the period of QS Vir could be represented by a linear ephemeris. The resulting O-C diagram shows a complex orbital period variation with semi-amplitude ~ 100 s. The second step was fitting the eclipse timings using a linear ephemeris plus a single light-travel time (LTT) effect. The residuals of this last fitting have a cyclic variation with semi-amplitude ~ 20 s. Finally, we fit the eclipse timings with the following equation,

$$T_{\min} = T_0 + E \times P + \tau_3 + \tau_4, \quad (1)$$

where T_0 , E and P are the epoch, the cycle count and the period of the binary, respectively, and τ_3 and τ_4 are the LTT effects (Irwin 1952). Each LTT includes five parameters:

semi-major axis, a , inclination, i , argument of periastron, ω , Keplerian mean motion, n , and epoch of periastron passage, T . We exclude from this analysis the mutual interaction between the external bodies. For the fitting we use the PIKAIA algorithm (Charbonneau 1995) to look for a global solution, followed by a Monte Carlo Markov Chain (MCMC) procedure to sample the parameters of Equation 1 around this solution. Figure 2 shows the result of this procedure and Table 2 shows the numerical values with the associated $\pm 68\%$ uncertainties.

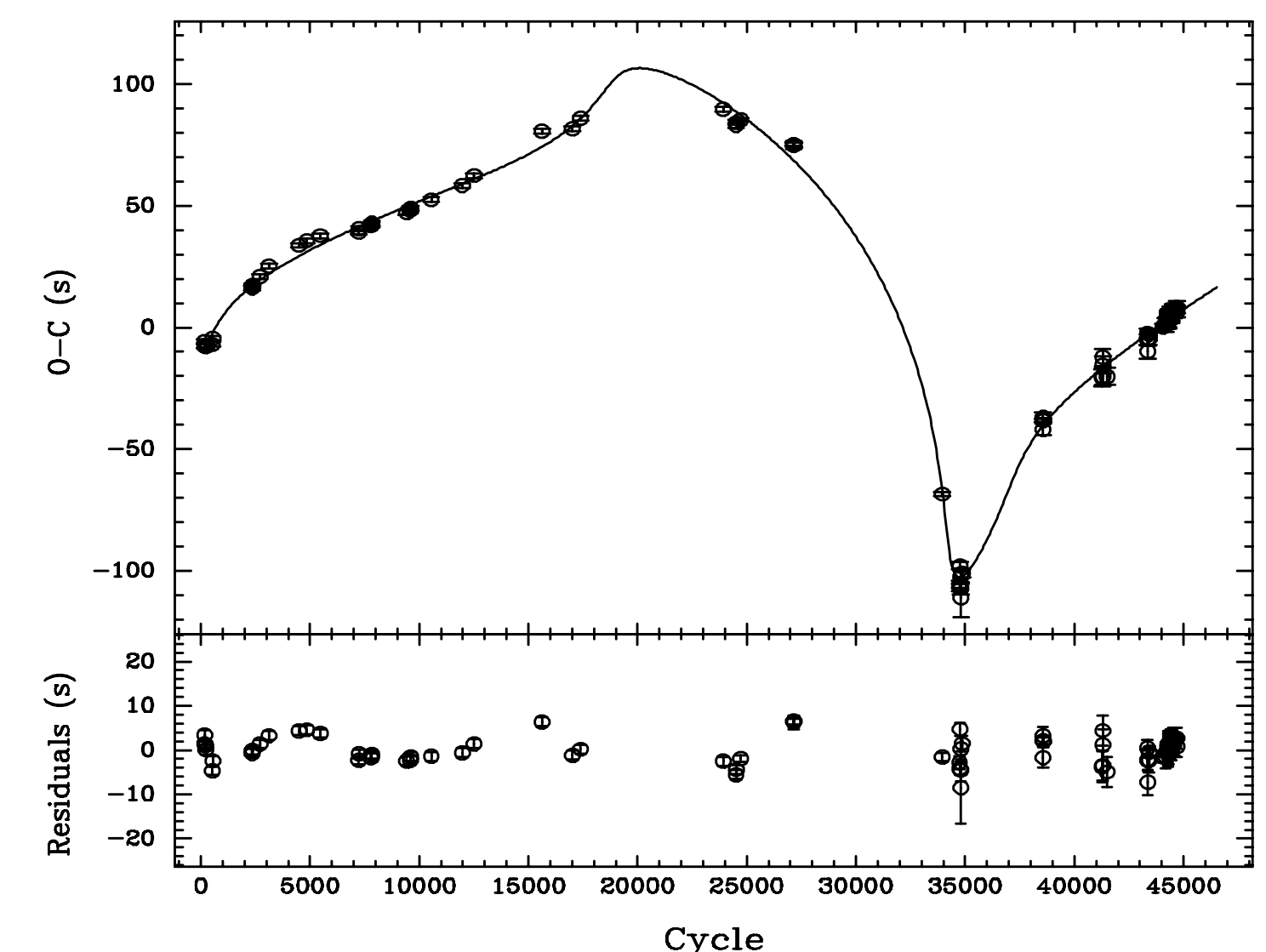


Figure 3: Upper panel: (O-C) diagram of the eclipse timings in QS Vir built with respect to the linear part of the ephemeris in Equation 1. The observed data are presented with open circles and the solid line represents the best fitting including the two LTT effects. Lower panel: The residuals around the fit.

Table 2: Parameters for the linear plus two-LTT ephemeris of QS Vir.

| Linear ephemeris | | |
|------------------|--------------------------------------|-----------|
| Parameter | Value | Unit |
| P | $0.150757478 \pm 2 \times 10^{-9}$ | days |
| T_0 | $2448689.14124 \pm 3 \times 10^{-5}$ | MJD(BTDB) |
| τ_3 term | | |
| Parameter | Value | Unit |
| P | 7.6 ± 0.23 | years |
| T | 54307 ± 30 | MJD(BTDB) |
| $a \sin i$ | 0.03 ± 0.0015 | AU |
| e | 0.62 ± 0.2 | |
| ω | 32.4 ± 1.6 | degrees |
| $f(M)$ | $(5.3 \pm 0.3) \times 10^{-7}$ | M_\odot |
| τ_4 term | | |
| Parameter | Value | Unit |
| P | 17.2 ± 0.22 | years |
| T | 53845 ± 10 | MJD(BTDB) |
| $a \sin i$ | 0.28 ± 0.015 | AU |
| e | 0.9 ± 0.2 | |
| ω | 213 ± 3 | degrees |
| $f(M)$ | $(7.8 \pm 0.2) \times 10^{-5}$ | M_\odot |

4. Discussion

Cyclic variations of the orbital period of compact binary systems in time-scales from years to decades can be explained by either the LTT effect or the Applegate mechanism. The LTT effect is a periodic variation and occurs because the distance from a binary to the observer varies due to gravitational interaction among the inner binary and the external body (Irwin 1952). The Applegate mechanism was proposed by Applegate (1992) and consists of the coupling between the binary period and changes in the shape of the secondary generated by the quadrupole momentum variation and consequently causing cyclic changes in the binary orbital period. Following the same method used by Brinkworth et al. (2006), we obtained that the required energy for the Applegate mechanism is larger than the total radiant energy of the secondary in 1 yr, considering the variation with semi-amplitude ~ 20 s. Thus, both τ_3 and τ_4 terms obtained by us could not be explained by the Applegate mechanism. Therefore, the only explanation for the observed periodic variations of the orbital period in QS Vir is the light-travel time effect by two outer bodies.

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