Physical parameters and orbital period variation of a newly discovered cataclysmic variable GSC 4560–02157

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Abstract GSC 4560–02157 is a new eclipsing cataclysmic variable with an orbital period of 0.265359 days. By using the published $V-$ and $R-$band data together with our observations, we discovered that the $O-C$ curve of GSC 4560–02157 may show a cyclic variation with a period of 3.51 years and an amplitude of 1.40 min. If this variation is caused by a light travel-time effect via the existence of a third body, then its mass can be derived as $M_3 \sin i' \approx 91.08\,M_{\rm Jup}$, and it should be a low-mass star. In addition, several physical parameters were measured. The color of the secondary star was determined to be $V-R = 0.77(\pm 0.03)$ which corresponds to a spectral type of K2–3. The secondary star's mass was estimated as $M_2 = 0.73(\pm 0.02)\,M_\odot$ by combing the derived $V-R$ value around phase 0 with the assumption that it obeys the mass-luminosity relation for main sequence stars. This mass is consistent with the mass$-$period relation for CV donor stars. For the white dwarf, the eclipse durations and contacts of the white dwarf yield an upper limit on the white dwarf's radius corresponding to a lower limit on mass of $M_1 \approx 0.501\,M_\odot$. The overestimated radius and previously published spectral data indicate that the boundary layer may have a very high temperature.

Key words: techniques: photometric — stars: binaries: cataclysmic variables — stars: individual: GSC 4560–02157

1 INTRODUCTION

Cataclysmic variables (CVs) are close binaries containing a low-mass main sequence star filling its Roche lobe and a white dwarf (Warner 1995). As the mass flows toward the white dwarf, an accretion disc around the white dwarf is formed. When a white dwarf is in an eclipsing CV, the eclipse times can be used to probe the companion object and its orbital evolution. The orbital periods of several CVs have exhibited cyclic changes which were interpreted as the presence of circumbinary companions, such as the cases of V2051 Oph (Qian et al. 2015), Z Cha (Dai et al. 2009) and OY Car (Han et al. 2015). The discovery of a companion object orbiting a CV has important implications for understanding extrasolar planet formation and evolution, since these binary systems form as a result of a common envelope phase (Andronov et al. 2003). In addition, the eclipsing CVs also provide a good opportunity to

measure their fundamental parameters and give some constraints on system structures.

GSC 4560–02157 is a newly discovered eclipsing CV (Khruslov et al. 2015). This CV was found to be a variable star from the Northern Sky Variability Survey Database (Woźniak et al. 2004) and attracted the attention of a researcher (Khruslov) in 2005. Khruslov et al. (2015) reported spectroscopic and many photometric observations, and the results show that GSC 4560–02157 is an eclipsing binary with a long orbital period of about 6.37 h. By using photometric observations, they found that the out-of-eclipse brightness demonstrates sensible changes but the primary eclipse was relatively stable. Moreover, its eclipse profile and spectral features are very similar to another long period eclipsing CV, GY Cnc.

Lastly, these authors confirmed that GSC 4560–02157 is an eclipsing CV. In the present paper, by using the data published by Khruslov et al. (2015), we obtained some basic system parameters and mid-eclipse times. Combining

these mid-eclipse times with our latest data, the linear ephemeris was revised and a cyclic variable in the $O − C$ diagram was found.

2 OBSERVATIONS AND DATA REDUCTION

GSC 4560–02157 was observed with a CCD photometer on the 50-cm (Apogee Alta U8300 with 528×512 pixels) telescope at the Sternberg Astronomical Institute Crimean Station on 2016 April 22 and 28. During the observations, the $R−$band was used. Aperture photometry was performed with the MAXIM DL package. All mid-eclipse times (including the data published by Khruslov et al. (2015)) were determined by using a parabolic fitting method because the light variations around those minima are nearly-symmetrical. All available CCD mid-eclipse times of GSC 4560–02157 are listed in Table 1.

Two eclipse profiles from our observation are displayed in Figure 1. For comparison, another two published eclipsing light curves are shown in Figure 2. These light curves exhibit a primary eclipse and features that are similar to an Algol-type eclipsing binary. However, the highly variable outside of the eclipse indicates that it is more likely to be an IP Peg-like or GY Cnc-like type. In addition, the secondary eclipse can be clearly seen in the light curve and the brightness variations on a variety of scales are superimposed on it.

3 RESULTS

3.1 Revised Ephemeris

Since its discovery, the changes in the orbital period have never been analyzed. By adopting photometric data from Khruslov et al. (2015), a total of 16 minima were obtained. Moreover, we also observed this target on 2016 April 22 and 28 and two mid-eclipse times were measured. All of the data are listed in Table 1. The $O − C$ values of all minima were computed with the following linear ephemeris

$$\text{Min.I} = \text{HJD } 2456594.0637 + 0.265359 \times E, \quad (1)$$

where HJD 2456594.0637 is the initial epoch from the first column in Table 1, 0.209937316 d is the orbital period from Khruslov et al. (2015), and E is the cycle number.

The newest $O − C$ diagram is shown in Figure 3. Overall, the $O − C$ curve shows possible cyclic variation, so a sinusoidal function can be considered to describe it. The result of the best-fitting is as follows

$$\begin{aligned} O − C = \ & 0.00112(\pm0.00042) \\ & +1.051(\pm0.026) \times 10^{-7} \times E \\ & +0.00097(\pm0.00026) \\ & \times \sin[0.0745°(\pm0.0006°) \times E \\ & -82.29°(\pm0.01°)], \end{aligned} \quad (2)$$

with $\chi^2 = 0.00032$ (the sum of squared residuals). Clearly, the sinusoid model displayed in Figure 3 is a good description. This equation indicates a cyclic change with an amplitude of 1.40 min and a period of 3.51 yr.

In Figure 3, the solid line in the upper panel refers to the best-fitting sine function, and the residuals are plotted in the lower panel.

3.2 Physical Parameters

In this section, some physical parameters will be calculated and discussed. Many $V−$ and $R−$band light curves of GSC 4560–02157 were published by Khruslov et al. (2015). However, only one system parameter was obtained, i.e. orbital period (0.265359 d). In principle, the $V − R$ color can be estimated by adopting $V−$ and $R−$band light curves. In the calculation process, the color index of primary minimum was used to determine the spectral type of the secondary star owing to the fact that the primary star and other light sources (including accretion disc and bright spot) were almost entirely eclipsed by the secondary star. Since the data from Khruslov et al. (2015) were analyzed by using the differential photometry method, the $V − R$ values of a comparison star are needed. The following formula,

$$\Delta V − \Delta R = (V − R) − (V − R)_C \quad (3)$$

was used to calculate the $V − R$ color. $(\Delta V − \Delta R)$ and $(V − R)_C$ in this formula are the color index from the differential photometry method and the comparison star, respectively. The comparison star is GSC 4560–01221 in the GSC2.3 catalog (Khruslov et al. 2015; Lasker et al. 2008). Its magnitudes in the $V−$ and $R−$bands are 14.33 and 14.11 mag, respectively. The values of $(\Delta V − \Delta R)$ are computed by using $V−$ and $R−$band light curves offered by Khruslov et al. (2015), which were acquired on 2014 April 25 and May 5. Lastly, the $V − R$ value around phase 0 was derived as $0.77(\pm0.03)$. Since the secondary star of GSC 4560–02157 may be a main sequence star, according to the MK spectral class system (Cox 2000, table 15.7), the spectral type could be roughly estimated as K2−K3 or even later, corresponding to $T_2 \leq 4600 − 4800$. Cox (2000) also gave the calibrated physical parameters for stars from various spectral classes (Cox 2000, table 15.8), and the mass-luminosity relation provides a mass of $M_2 \approx 0.73(\pm0.02) M_\odot$ for K2−3 type. The mass-radius relationship of CVs will be roughly (Knigge 2011)

$$R_2/R_\odot = f(M_2/M_\odot)^\alpha \quad (4)$$

with $f \simeq \alpha \simeq 1$. $M_2 \approx 0.73 M_\odot$ corresponds to $R_2 \approx 0.73 R_\odot$. For comparison, we put this value in the mass−period relation of CV donor stars. As shown in Figure 4, the location of this donor (the asterisk) is compatible with the overall trend.

For the white dwarf, theoretically, its parameters can be derived from eclipsing CVs if eclipse contacts of the

Table 1 New CCD Mid-eclipse Times of GSC 4560–02157

Min. (HJD)	Err	E	$O - C$	Filter	Duration	Reference
2456374.34671	0.00018	–828	–0.00022	R	0.0356	[1]
2456591.14506	0.00025	–10	–0.00027	R	0.0364	[1]
2456594.06374	0.00013	0	0.00000	R	0.0318	[1]
2456716.39552	0.00020	461	0.00128	R	0.0305	[1]
2456717.19129	0.00012	464	0.00097	R	0.0318	[1]
2456717.45713	0.00016	465	0.00146	R	0.0318	[1]
2456718.25249	0.00015	468	0.00075	R	0.0319	[1]
2456719.31423	0.00018	472	0.00105	R	0.0305	[1]
2456720.37540	0.00020	476	0.00078	R	0.0342	[1]
2456722.49900	0.00019	484	0.00151	R	0.0354	[1]
2456728.33652	0.00018	506	0.00113	R	0.0332	[1]
2456745.31881	0.00031	570	0.00044	V	0.0321	[1]
2456772.38606	0.00011	672	0.00107	R	0.0341	[1]
2456772.38629	0.00028	672	0.00130	V	0.0334	[1]
2456782.20444	0.00034	709	0.00120	R	0.0342	[1]
2456782.20447	0.00087	709	0.00117	V	0.0304	[1]
2457501.33114	0.00033	3419	0.00498	R	0.0343	[2]
2457507.43412	0.00029	3442	0.00471	R	0.0360	[2]

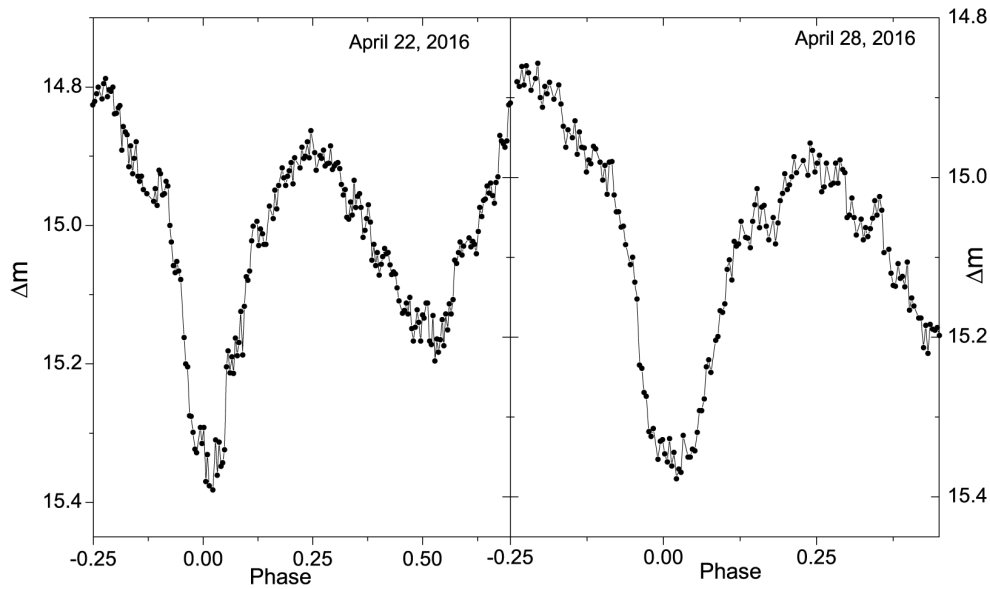References: [1] Khruslov et al. 2014; [2] Our data.

Fig. 1 Two eclipsing profiles of GSC 4560–02157 are shown. The data were observed by using the 50 cm telescope at the Sternberg Astronomical Institute Crimean Station in 2016.

white dwarf can be measured precisely. However, the radial velocities of the two components are unknown. To resolve this problem further, the eclipse duration and contact of the white dwarf can be considered to determine radii of the stars. For eclipse durations, the eclipse profiles from Khruslov et al. (2015) are almost symmetric and have a relatively flat bottom, suggesting that the white dwarf should be the center of the bright source. Therefore, the durations can be determined by locating the extreme values of the eclipse curve derivative. This method was described by

Wood et al. (1985). First, the observed light curves were smoothed with a median filter and differentiated numerically. Second, the derivative curves were used to locate the extreme points.

This measurement procedure is illustrated in Figure 5. All durations were measured and are listed in the sixth column of Table 1. However, the eclipse contacts of the white dwarf are very difficult to determine because of the boundary layer and a hot inner-disc region around the white dwarf. Fortunately, a well-defined egress profile of
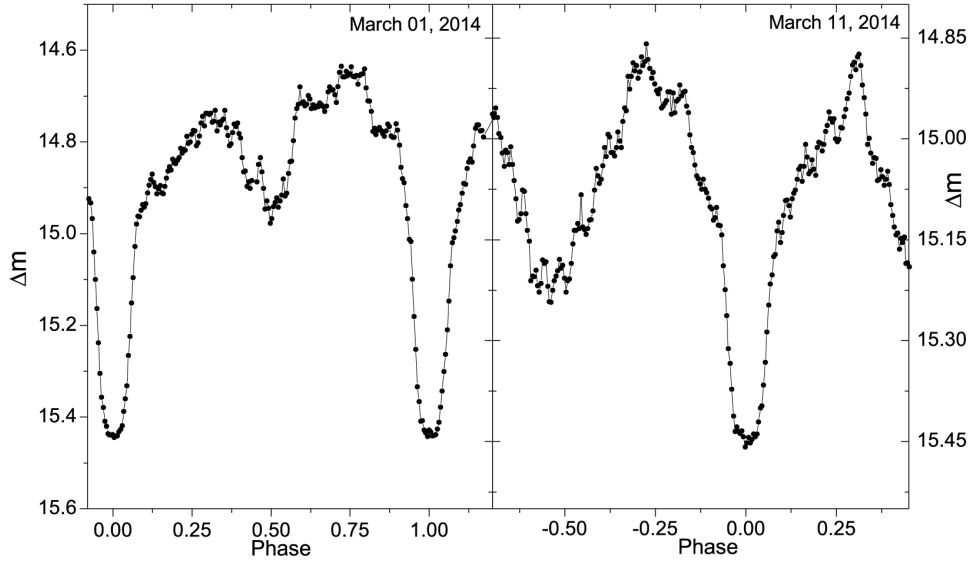
Fig. 2 The data from Khruslov et al. (2015). These light curves exhibit a strong change in the out-of-eclipse brightness.
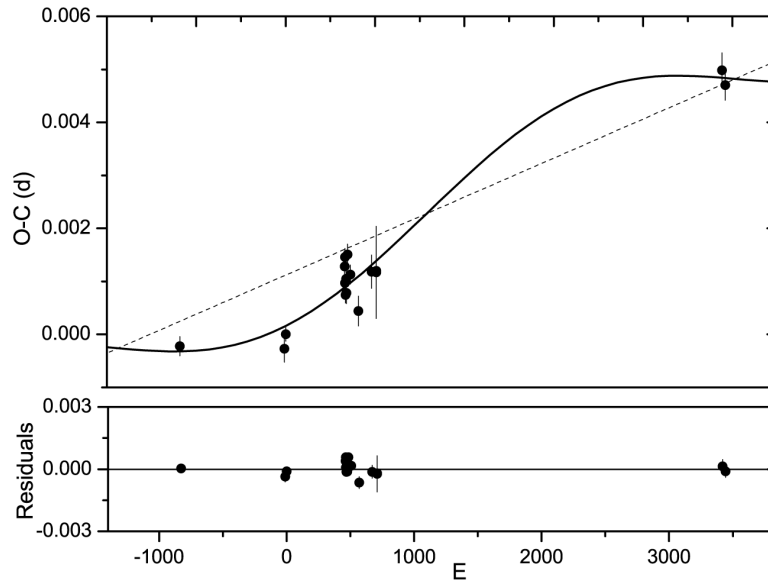

Fig. 3 $O - C$ diagrams of GSC 4560–02157. The solid line in the upper panel refers to a cyclic change. The dashed line represents a revised linear ephemeris. After both of these were removed, the residuals are plotted in the lower panel.

the white dwarf was observed (see Fig. 6). This eclipse profile has two distinct steps corresponding to the occultation of the white dwarf and bright spot. These features are similar to some typical eclipsing dwarf novae such as OY Car (Wood et al. 1989) and Z Cha (Wood et al. 1986).

As shown in Figure 6, $\Delta\tau$ refers to the duration, and τ_1 and τ_2 are the start and end times of the white dwarf egress, respectively. It should be noted that the white dwarf's ingress is not used to measure the start and end times of the white dwarf's ingress because the ingress times of the white dwarf and bright spot are almost simultaneous. The

radii of both components were derived by using the following equations:

$$R_1 = \frac{v_1 + v_2}{2}(\tau_2 - \tau_1) \tag{5}$$

and

$$R_2 = \frac{v_1 + v_2}{2}\Delta\overline{\tau}, \tag{6}$$

where v_1 and v_2 refer to the radial velocity of the primary and secondary stars respectively, and $\Delta\overline{\tau}$ is the average value of all durations in Table 1. Combining Equations
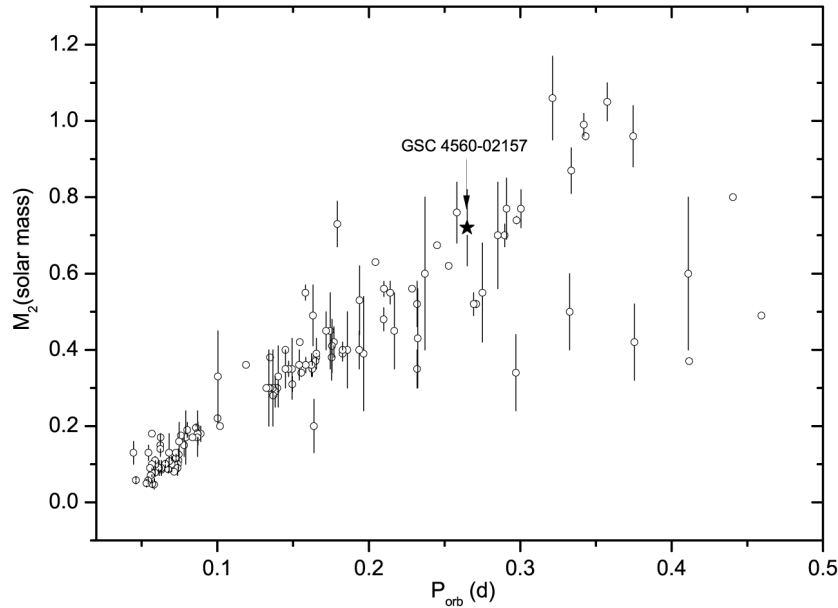
Fig. 4 Mass-period relation of CV donor stars. Data are from the latest version (update RKcat7.23, 2015) of the Ritter & Kolb (2003) catalog. The asterisk marks the location of GSC 4560–02157.
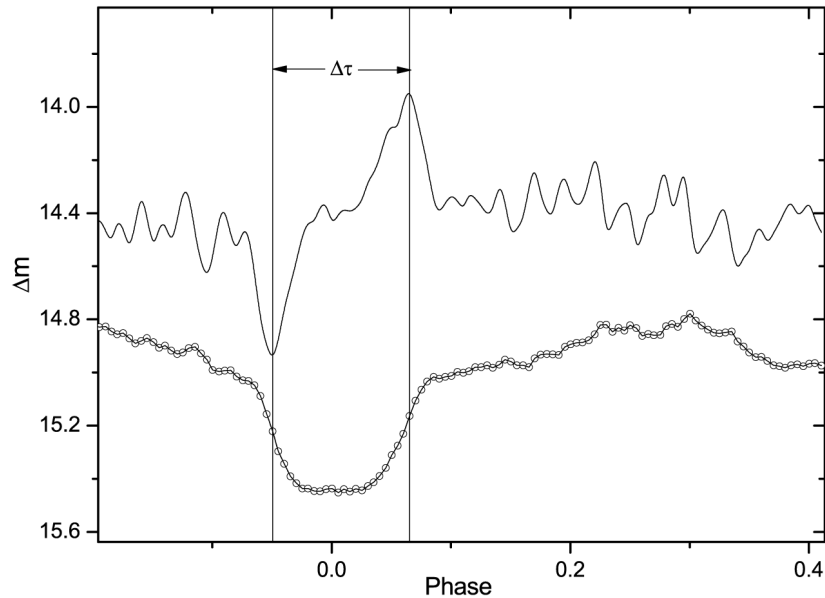

Fig. 5 Example of determining eclipse durations. The interval marked by solid lines represents the durations.

(5) and (6) immediately yields the white dwarf's radius as $R_1 \approx 0.0234\,R_\odot$. During the calculation, $\tau_2 - \tau_1 \approx 1.57$ min was used.

If we use the mass-radius relation for white dwarfs to estimate the mass in this case (Nauenberg 1972), $0.0234\,R_\odot$ corresponds to $0.225\,M_\odot$. In the mass−period diagram, this value is much lower than all CVs with $P_{\rm orb} > 0.2$ d, and is also too small from an evolutionary perspective. There are several reasons why a white

dwarf's radius may be overestimated. One is that the white dwarf could have a 'thick' boundary layer or atmosphere due to its high accretion rate (see Sect. 4). Another reason is supposing that the orbital inclination equals 90° during the calculation. Parsons et al. (2010) accurately measured mass and radius of a white dwarf that is part of a pre-CV NN Ser independently of any mass-radius relation. They gave the values as $R_1 = 0.0211\,R_\odot$ and $M_1 = 0.535\,M_\odot$, and also calculated the surface gravity of the white dwarf
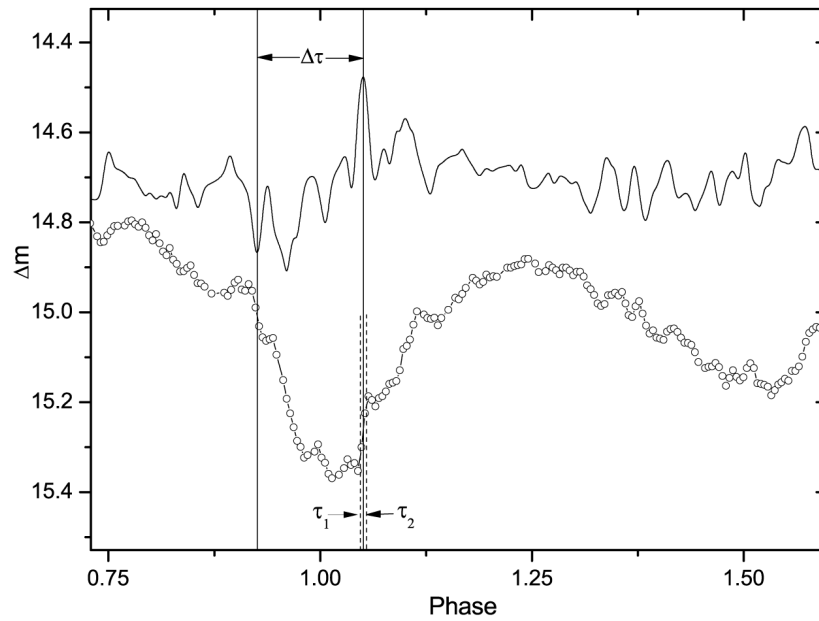
Fig. 6 A sample measuring the contacts of the white dwarf. The two dashed lines signify the start and end times of the white dwarf egress, on the left and right respectively.
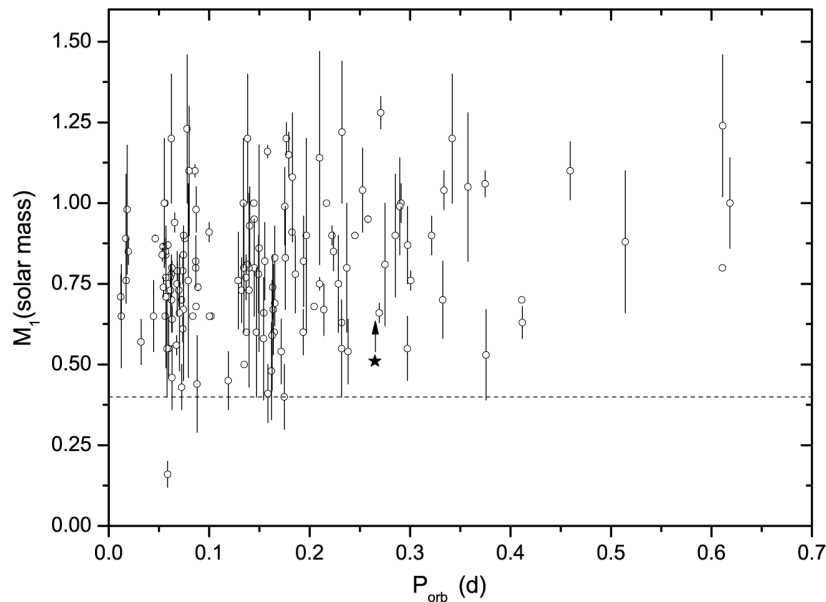

Fig. 7 Mass-period relation of CV primary stars. Data are from the latest version (update RKcat7.23, 2015) of the Ritter & Kolb (2003) catalog. The relative position of the white dwarf of GSC 4560–02157 is marked with an asterisk.

as $\log g = 7.74$. This value may be a reasonable approximation for the white dwarf of GSC 4560–02157. Adopting $\log g = 7.74$ for GSC 4560–02157, the mass of the white dwarf can be estimated as $M_1 \approx 0.501\,M_\odot$. However, this value for the white dwarf's mass ($0.501\,M_\odot$) is only a lower limit corresponding to an upper limit on its radius.

Figure 7 shows the position of this lower limit in the mass−period relation of CV primary stars.

4 DISCUSSION AND CONCLUSIONS

Monitoring the mid-eclipse times of CVs provides insight into their orbital evolution. As noted above, the $O - C$ curve of GSC 4560–02157 may show a cyclic change with a period of 3.51 yr. The likely explanations for this cyclic variation are either solar-like magnetic activity in the secondary star (Applegate 1992) or a third body in the system. Most CVs with period modulations can be found from

Table 2 The Orbital Parameters of the Third Body in GSC 4560–02157

Parameter	Value and Uncertainty	Unit
Period (P_3)	3.51 ± 0.01	yr
Eccentricity (e_3)	0	
Amplitude (K_3)	1.40 ± 0.02	min
a_3 ($i' = 90°$)	2.81 ± 0.52	AU
$M_3 \sin i'$	91.08 ± 34.02	$M_{\rm Jup}$
$f(m)$	$3.85\pm(2.4)\times10^{-4}$	$M_\odot$

Pilarčík et al. (2012). If the periodic change of the $O - C$ diagram is caused by a companion orbiting GSC 4560–02157, then the mass function and the mass of this companion can be computed by using the following equation

$$
\begin{aligned}
f(m) &= \frac{4\pi^2}{GP_3^2}(a'_{12}\sin i')^3 \\
&= \frac{(M_3 \sin i')^3}{(M_1 + M_2 + M_3)^2},
\end{aligned}
\tag{7}
$$

where G is the gravitational constant, P_3 is the period of the $O - C$ oscillation and $a'_{12}\sin i'$ can be determined by

$$
a'_{12}\sin i' = K_3 \times c.
\tag{8}
$$

K_3 is the semi-amplitude of the $O - C$ oscillation, i.e.

$$
a'_{12}\sin i' = 0.168(\pm0.03)\,\text{AU}.
$$

By using the parameters from Section 3.2, the mass function and the mass of the third body were derived as

$$
f(m) = 3.85(\pm2.4) \times 10^{-4}\,M_\odot
$$

and

$$
\begin{aligned}
M_3 \sin i' &= 0.087(\pm0.032)\,M_\odot \\
&\approx 91.08\,M_{\rm Jup} > 0.075\,M_\odot.
\end{aligned}
$$

Clearly, this is a low-mass star. The parameters of the tertiary component are displayed in Table 2. However, a large error range of this companion mass means it may be a brown dwarf with a small probability. As expected, no long-term change in the $O - C$ curve was discovered. The main reason for this is that the time span of the data is less than 3 years.

Additionally, combining the published $V-$ and $R-$band data with our observations, several physical parameters can be obtained. The derived mass of the donor star is about $0.73(\pm0.02)\,M_\odot$, consistent with the mass$-$period relation of CV donor stars. As noted above, the measured radius of the white dwarf is likely to be overestimated. A spectroscopic observation at the phase 0.505 published by Khruslov et al. (2015) shows very obvious HeI and HeII emissions. Szkody et al. (2009) pointed out that the HeII 4686 line is a strong indicator of high accretion. This means the boundary layer has a very high

temperature and the disc is relatively much brighter. The inner disc may have a compact structure surrounding this white dwarf (Hoare & Drew (1991)). In addition, we have assumed that the orbital inclination is $90°$ in the computing process. Therefore, we obtained the upper limit of the white dwarf radius, corresponding to the lower limit of mass. Certainly, much longer photometric monitoring for GSC 4560–02157 in the future is required in order to ascertain its nature in terms of orbital evolution, the structure of the system and possible reasons for cyclic variations in the $O - C$ curve.

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