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Two Massive Twins in a Deep-contact Binary with a Black Hole Candidate

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Abstract

New light curves in B, V, R, and I bands for the B-type contact binary V593 Cen were obtained, and another V-band light curve was collected from All Sky Automated Survey data. We analyzed these two sets of light curves using the Wilson–Devinney code. It was found that V593 Cen is a deep-contact binary with a fill-out factor of more than 45%. The mass ratio, derived to be nearly one from light curves, indicates that this system contains two twin components. Together with the higher temperature of the less-massive component, it is inferred that the system has just passed the mass-reversal stage during the mass-transfer evolution. Therefore, at present it has the shortest period and deepest-contact configuration. By analyzing all available eclipse times, it is found that the $O-C$ curve of V593 Cen shows a cyclic variation with a period of 50.9 yr. This can be explained as the light-travel time effect via the presence of a third body. The mass of the third body is derived to be larger than 4.3 ($\pm$0.3) $M_{\odot}$, and it should contribute to the total light of the system. However, no third light is detected during the photometric analyses. This indicates that it may be a black hole candidate orbiting the central mass-transferring binary in a triple system. During the evolution of this hierarchical triple-star system, the "eccentric Kozai–Lidov" mechanism may play a major role in the formation of the inner contact binary. This system seems a perfect candidate to be one of "merged" systems mentioned by Naoz & Fabrycky.

Key words: binaries: close – binaries: eclipsing – stars: early-type – stars: evolution – stars: individual (V593 Cen)

Supporting material: data behind figures

1. Introduction

V593 Cen (TYC 8994-44-1, CPD -61° 3558) is a short-period early-type binary, which was found to be a variable star by Shapley & Swope (1940) and classified as a W UMa-type binary by Van Gent (1948), who gave an ephemeris based on his photographic times of light minimum of

$$\mathrm{MinI} = \mathrm{HJD}\ 2427621.2693(\pm 0.0024) + 0\overset{\mathrm{d}}{.}7553542(\pm 0.0000028) \times E \qquad (1)$$

where E is the circle number from the initial minimum. Lyngå (1970) classified its spectral type as B1 by using the spectrograph equipped on a 100 cm reflector telescope. Nearly 20 years later, Lapasset et al. (1988) inferred that the spectral type is B5 from its color–color diagram and pointed out that V593 Cen is a new early-type contact binary. Based on 18 photoelectric minima, they revised the ephemeris as

$$\mathrm{MinI} = \mathrm{HJD}\ 2445815.564(\pm 0.00017) + 0\overset{\mathrm{d}}{.}755355990(\pm 0.00000018) \times E. \qquad (2)$$

After than, apart from some eclipse times (e.g., Dvorak 2004), there are no further investigations of this early-type binary.

V593 Cen is one of a small group of B-type contact binaries with periods of shorter than one day. Some other members in this group contain V701 Sco (Bell & Malcolm 1987; Qian et al. 2006), RZ Pyx (Zhao et al. 2018a), CT Tau (Plewa & Wlodarczyk 1993), BH Cen (Zhao et al. 2018b), BR Mus (Lapasset et al. 1987b), and so on. These binaries have more massive components and longer periods compared to their cool cousins, W UMa-type contact binary stars, whose components are FGK-type stars with a typical period about $P = 0.29$ day (Qian et al. 2017). The investigation of this small group of B-type short-period binaries can provide valuable information on the evolution state of close binary systems. On the other hand, because the magnetic activity cycles could be ruled out of explaining the cyclic variation in the $O-C$ diagram, these systems are a good source within which to search for third-body orbiting close binary stars by using the light-travel-time effect (e.g., Qian et al. 2008). In this Letter, multi-color charge-coupled device (CCD) photometric light curves of V593 Cen in B, V, R, and I bands are presented, then the orbital period variations and those new photometric data were analyzed. Finally, based on the period changes and photometric properties, the triplicity, formation, and evolutionary states of the binary all were investigated.

2. New Observations and Period Analysis

The first photoelectric light curves for V593 Cen in UBV bands were presented and analyzed by Lapasset et al. (1987a). Different solutions, corresponding to values of the mass ratio between 0.60 and 1.90, were presented. But there was no accurate light curves from then on. We observed V593 Cen from 2016 April to 2017 April using a CCD camera attached to the 0.6 m robotic telescope (PROMPT-8),[6] located in Cerro Tololo of Chile. During the observations, the B, V, R and I filter system close to the Bessel

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[6] PROMPT-8 was built by the University of North Carolina at Chapel Hill based on the collaboration with National Astronomical Research Institute of Thailand (NARIT). It is operated by SKYNET (http://skynet.unc.edu)—a distributed network of robotic telescopes located around the world, dedicated to continuous gamma-ray burst afterglow observations.

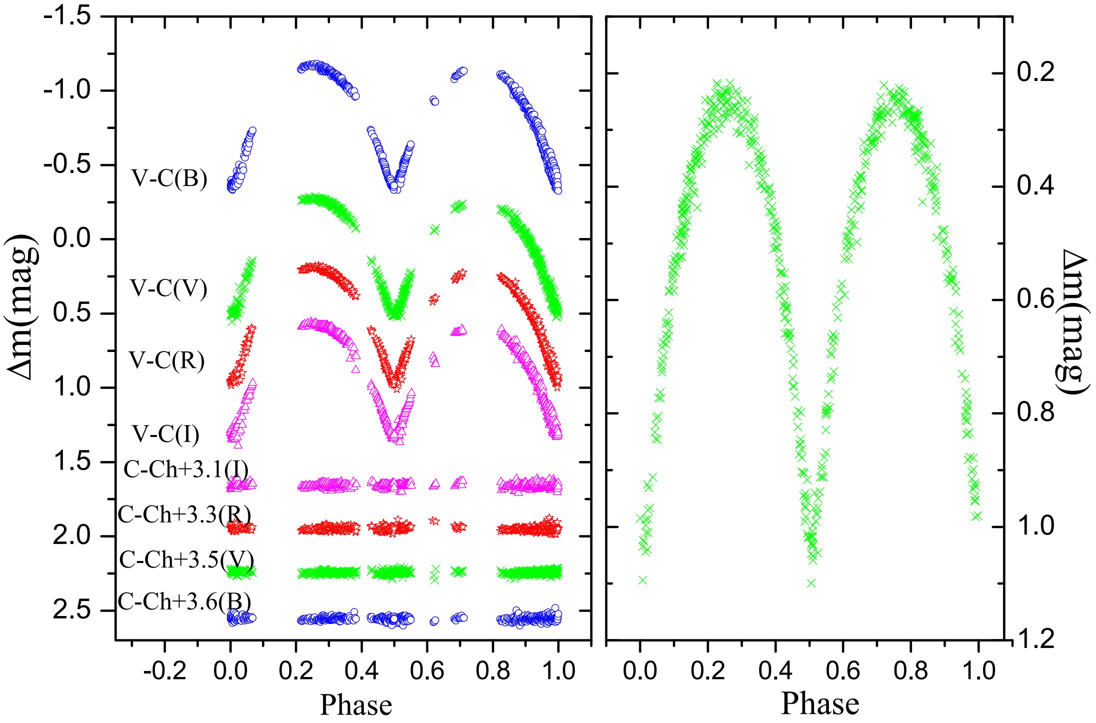

Figure 1. New light curves for V593 Cen. Left panel: *BVRI* light curves observed by PROMPT-8. Right panel: light curve (Mag-10) in the *V*-band from the ASAS database. The data used to create this figure are available.

system was employed. Before we measured the magnitude, standard bias and sky-flat were used to reduce all frames. When reducing the observed images, the PHOT package of the Image Reduction and Analysis Facility (IRAF)[7] was adopted. Two stars close to V593 Cen were chosen as the comparison and check stars, which were as bright as the target.[8] Their coordinates are $\alpha_{2000} = 13^{h}17^{m}05\overset{s}{.}3$, $\delta_{2000} = -62°33'36\overset{\prime\prime}{.}7$ and $\alpha_{2000} = 13^{h}16^{m}37\overset{s}{.}9$, $\delta_{2000} = -62°37'05\overset{\prime\prime}{.}6$.

We checked observations in many databases and found that V593 Cen was observed in the All Sky Automated Survey (ASAS[9]) by Pojmanski & Maciejewski (2004). ASAS measured the magnitude in the *V*-band by using small automated instruments. During more than 3000 days from Hel JD 2451877 (2000 November) to 2455087 (2009 September), this binary was observed in more than 600 frames, covering all phases by one instrument. We chose all high-precision data with grades better than "c." The phases of those data were calculated by using the same ephemeris as our observations from PROMPT-8: Hel JD $2457781.8433 + 0\overset{d}{.}7553457 \times E$. All of the light curves from the two telescopes are shown in Figure 1.

To investigate the period changes of V593 Cen, all available photographic, photoelectric, and CCD times of light minimum were collected and are shown in Figure 2.[10] Those shown in the second column are the observational methods, where "pg" refers to photographic, "pe" to photoelectric, and "CCD" to charge-coupled device. The $(O - C)$ values of V593 Cen were formed using the linear ephemeris from the $O - C$ gateway,[11]

$$\mathrm{MinI} = 2427621.2693 + 0\overset{d}{.}7553556 \times E. \tag{3}$$

The $(O - C)$ values are shown in the fourth column of the supplementary data table and the corresponding $(O - C)$ diagram is plotted against the epoch number in the upper panel of Figure 2. It is obvious that the orbital period of V593 Cen is variable. As displayed in the upper panel of Figure 2, the general trend of the $(O - C)_1$ shows a linear change plus a cyclic oscillation. With weight 1 for photographic data and weight 8 for photoelectric and CCD observations, a least-squares solution leads to the following ephemeris:

$$\begin{aligned}\mathrm{MinI} = {} & 2427621.2082(\pm 0.0054) \\ & + 0\overset{d}{.}7553577(\pm 0.0000002) \times E \\ & + 0.057(\pm 0.004)\sin[0\overset{\circ}{.}0146 \times E + 76\overset{\circ}{.}6].\end{aligned} \tag{4}$$

The sinusoidal term in Equation (4) reveals a cyclic change with a period of $P_3 = 50.9$ yr and an amplitude of $A_3 = 0.057$ day. It is more easily seen in the upper panel of Figure 2. The residuals from the equation are displayed in the low panel of the figure, where no variations can be traced indicating that Equation (4) describes the general trend of the $O - C$ curve well.

3. Photometric Solutions

The Wilson–Devinney Codes (W–D) have improved in the many versions that have been published since the first in 1971 (Wilson & Devinney 1971; Wilson 1990, 1994; Van Hamme & Wilson 2003; Wilson 2012 and so on), and it has became the

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[7] IRAF is a general purpose software system for the reduction and analysis of astronomical data. IRAF is written and supported by the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona.

[8] All data obtained from PROMPT-8 is listed in the supplementary data.

[9] http://www.astrouw.edu.pl/asas/

[10] All of these minima are list in the supplementary data.

[11] http://var2.astro.cz/ocgate/

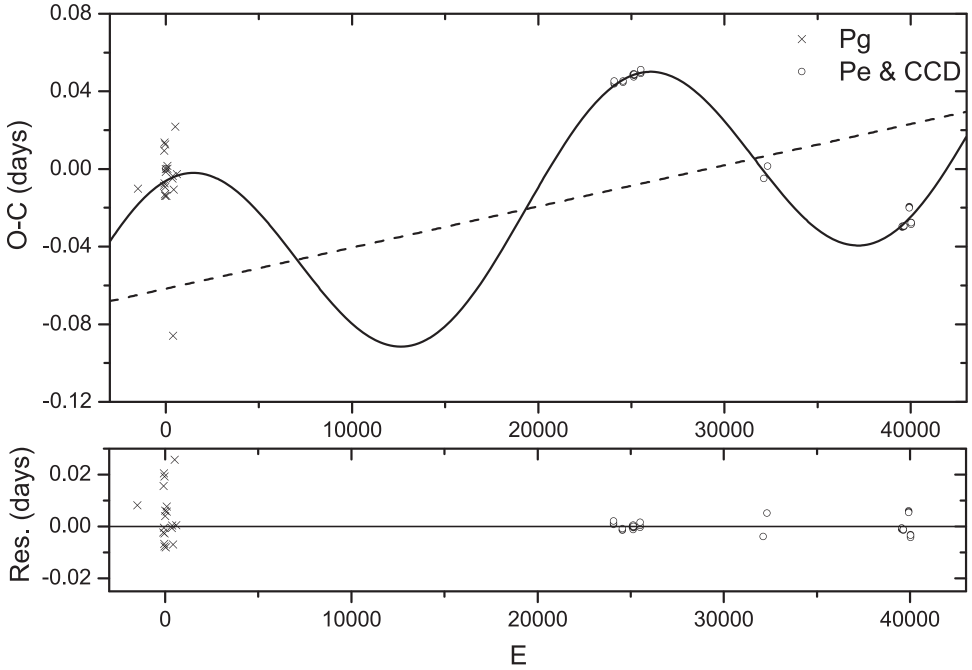

Figure 2. Period change of V593 Cen. Upper panel: the dashed line represents the fitting straight line, and the solid line shows the periodic fitting in Equation (4). Bottom panel: the residual. The data used to create this figure are available.

most widely used method for analyzing the light curves of eclipsing binaries. The new *BVRI* multi-color light curves of V593 Cen are analyzed with the latest version of W–D code. According to its spectral type of B5 classified by Lapasset et al. (1988), we applied the effective temperature of primary $T_1 = 15{,}000$ (Cox 2000). There were no mass ratios from radial velocity before, so we used the q-search method to search for an initial mass ratio first. We fixed the mass ratio (q) at a series of values from 0.6 to 1.6 and then acquired convergent solutions at each value. The results are shown in the upper panel of Figure 3. From the relation between q and the residuals ($\Sigma(O-C)^2$), the optimal mass ratios for the two light curves should be $q = 1.05$ and $q = 1.1$, respectively. Then, we set the q as a free parameter and obtained the final solutions. During the whole process, the bolometric albedo $A_1 = A_2 = 1.0$ (Rucinski 1969) and the gravity-darkening coefficient $g_1 = g_2 = 1.0$ (Lucy 1967) were used. The contact model (model 3) was chosen. The adjustable parameters are listed as follows: the mass ratio q; the orbital inclination i; the temperature of secondary T_2; the luminosity of primary component L_1; and so on. The photometric solutions are listed in Table 1 and the theoretical light curves computed with those photometric elements were plotted in the bottom panel of Figure 3. As shown in Table 1, the solutions from two sets of light curves are nearly the same.

Table 1
The Solutions of V593 Cen Using W–D Code

Parameters	PROMPT-8	ASAS
g_1(fix)	1.0	1.0
g_2(fix)	1.0	1.0
A_1(fix)	1.0	1.0
A_2(fix)	1.0	1.0
T_1(fix)	15000 K	15000 K
$q(M_2/M_1)$	1.05	1.05
T_2	15099 ± 23 K	15011 ± 77 K
$i(°)$	82.6 ± 0.9	82.6 ± 0.3
$L_1/(L_1+L_2)_B$	0.4877 ± 0.0003	…
$L_1/(L_1+L_2)_V$	0.4880 ± 0.0004	0.480 ± 0.0012
$L_1/(L_1+L_2)_R$	0.4882 ± 0.0005	…
$L_1/(L_1+L_2)_I$	0.4884 ± 0.0008	…
$\Omega_1 = \Omega_2$	3.57	3.57
r_1(pole)	0.3853 ± 0.0003	0.387 ± 0.010
r_1(side)	0.4113 ± 0.0003	0.415 ± 0.012
r_1(back)	0.4649 ± 0.0004	0.474 ± 0.010
r_2(pole)	0.3910 ± 0.0011	0.396 ± 0.042
r_2(side)	0.4180 ± 0.0014	0.423 ± 0.057
r_2(back)	0.4700 ± 0.0027	0.480 ± 0.110
filling(%)	45.4 ± 1.1	53.0 ± 3.5
$\sum(O-C)_i^2$	6.22×10^{-3}	4.71×10^{-3}

4. Discussion and Conclusion

We analyzed the two sets of light curves of V593 Cen from our new observations and ASAS database by using the W–D code and obtained the photometric solutions. Based on the solutions, the mass ratio of the system (M_2/M_1) was determined to be 1.05, indicating that the primary component is the less-massive one with a slightly higher temperature. According to the spectral type B5, the mass of the primary component is estimated as $M_1 = 5.9\,M_\odot$ (Cox 2000), while that of the secondary component could be calculated as $M_2 = 6.2\,M_\odot$ by using the derived mass ratio. The orbital inclination i is about $82\overset{\circ}{.}6$, revealing that V593 Cen is a total eclipsing binary. This indicates that the determined photometric parameters are reliable. It is detected that the system is an over-contact binary with a fill-out factor about 45.4%, where both components are sharing a common radiative envelope. By using *Kepler*'s third law with the photometric solution, the evolutionary locations of both components for this early-type

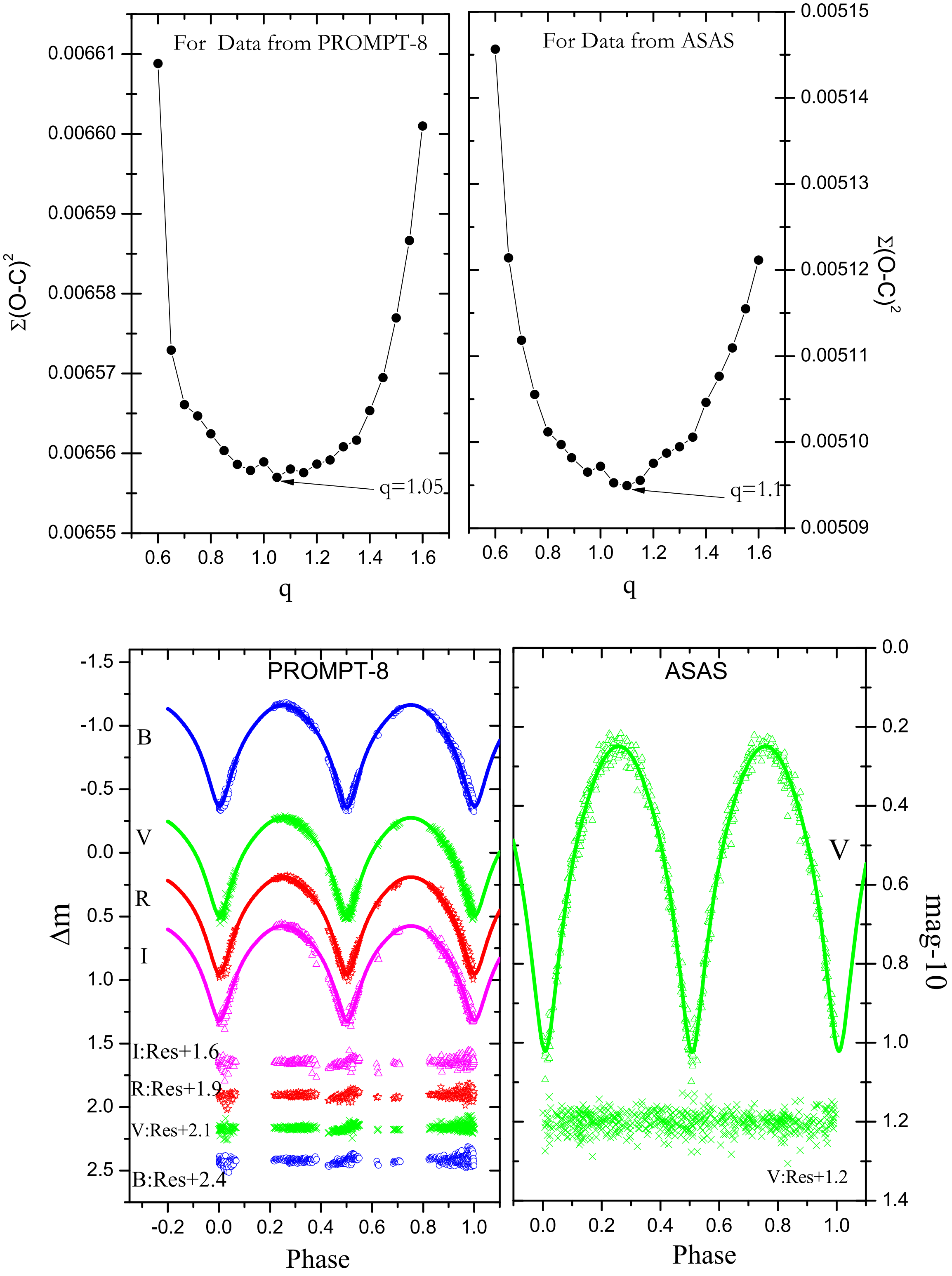

Figure 3. Photometric solutions for new light curves for V593 Cen. Top panel: mass-ratio search for these two sets of light curves. Bottom panel: theoretical light curve (solid lines in different colors) and residuals (below the light curves).

binary V593 Cen are given in Figure 4, where the evolutionary tracks and isochrones for solar chemical compositions are taken from Girardi et al. (2000). From the evolutionary locations of two components, we could see that they are both nearly at the same place and their age is about 1.1×10^8 yr.

Based on those observational properties, we infer that the early-type contact binary V593 Cen is in a special evolutionary stage during the mass transfer of the binary. The progenitor of V593 Cen is a short-period detached binary, where the original primary component evolves fast and fills the critical Roche lobe first. It transfers mass to the secondary component, and then causes the orbital period to decrease and the mass ratio of the system to increase. When both components have identical masses ($q = 1$) during the mass transfer, the period of the

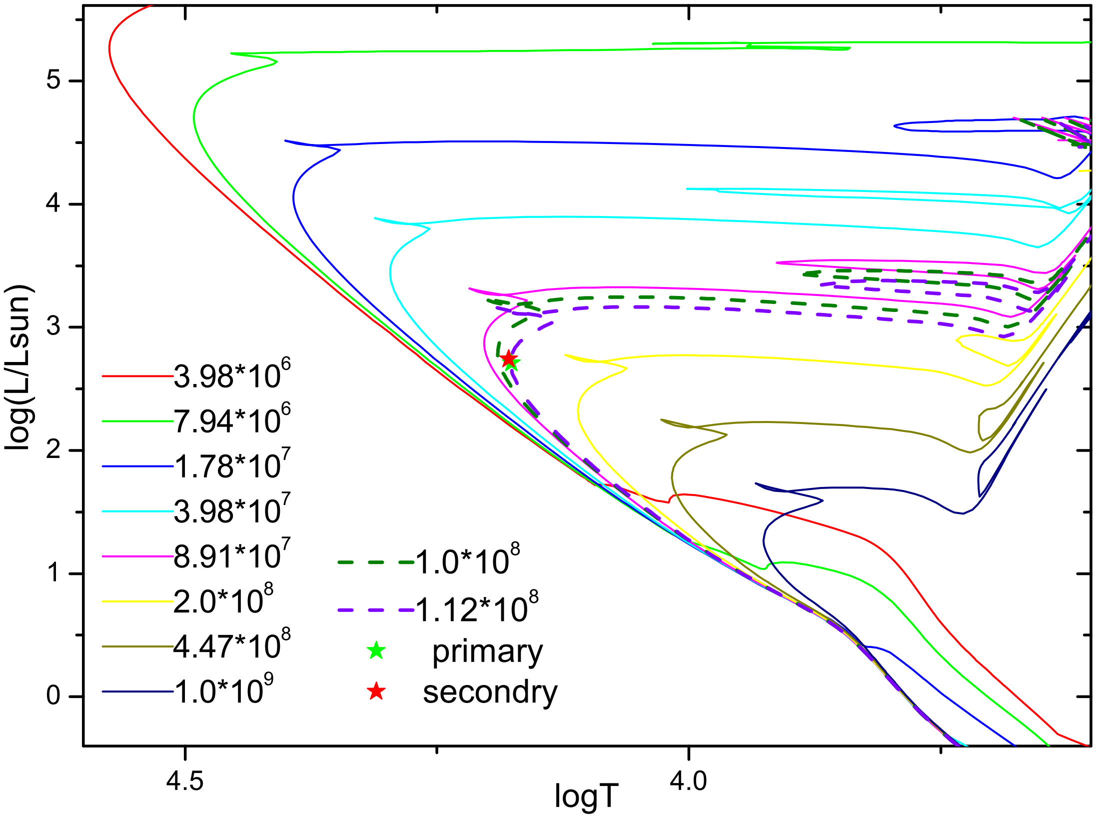

Figure 4. Evolutionary locations of both components of V593 Cen.

system is the shortest and the binary may have a deep-contact configuration. The derived mass ratio and the deep-contact configuration of V593 Cen may suggest that it has just passed the shortest period stage during the Case A mass transfer. The current less-massive star is the original more massive one in the initially detached system. It has lost some hydrogen material and has a slightly higher temperature. The situation of V593 Cen is similar to that of V753 Mon. Qian et al. (2013) pointed out that V753 Mon is in a key evolutionary stage, just after the shorter period stage during the mass transfer. However, V753 Mon is a semi-detached binary, while V593 Cen is an over-contact system.

The two components in V593 Cen are early-type stars that contain the convective core and the radiative envelope. This suggests that the period oscillation cannot be explained by the magnetic activity cycle mechanism, which is usually adopted to explain the cycle period change of later-type binary stars (e.g., Applegate 1992; Lanza et al. 1998). Therefore, the light-travel-time effect via the presence of a tertiary body is adopted to explain the cyclic change of the orbital period (e.g., Irwin 1952; Chambliss 1992; Borkovits & Hegedüs 1996; Liao & Qian 2010). Using this method, tertiary bodies have been detected orbiting massive close binary stars. Some examples are V701 Sco (Qian et al. 2006), V382 Cyg, TU Mus (Qian et al. 2007), and AI Cru (Zhao et al. 2010). Though it seems that binaries favor a more uniform distribution of eccentricities (Tokovinin 1997, 2008; Raghavan et al. 2010; Moe & Di Stefano 2017), we still assume that the tertiary wanders in the circular orbit. This is because the period change (in Figure 2) displays a periodic oscillation, and this oscillation is fitted either by a sine curve without eccentricities, or by using the value of the outer orbital period and the inner binary period (P_{outer} and P_{inner}). The period ratio for this multiple system is about $P_{\mathrm{outer}}/P_{\mathrm{inner}} = 2.5 \times 10^4$. For this kind of multiple star system with a very large period ratio, the outer orbit usually has very low or no eccentricities (Shatsky 2001; Tokovinin 2004, 2008). Moreover, in large $P_{\mathrm{outer}}/P_{\mathrm{inner}}$ ratio multiple system (commonly found in triple systems) the Kozai effect becomes too weak (Tokovinin 2008). For brevity, considering that the third body in the V593 Cen system is moving in a circular orbit, the projected radius of the orbit of the eclipsing pair rotating around the mass central of the triple system, the mass function, and the masses of the third component could be computed with these equations as follows:

$$a'_{12}\sin i' = A_3 \times c \tag{5}$$

$$f(m) = \frac{4\pi^2}{GP_3^2} \times (a'_{12}\sin i')^3 = \frac{(M_3 \sin i')^3}{(M_1 + M_2 + M_3)^2}, \tag{6}$$

where A_3 is the amplitude of the $O - C$ oscillation, c is the light speed, P_3 is the period of the $O - C$ oscillation, and i' is the inclination of the tertiary orbital plane. Finally, when the inclination $i' = 90°$, it is calculated that the lowest mass of the tertiary companion is 4.3 (0.3) $M_{\odot}$ and the separation between the binary and the tertiary companion is about 25.5 (2.2) au. For the other inclinations, the third body should have a larger mass and a shorter separation. When the inclination $i' = 82\overset{\circ}{.}6$, which shows that the third body is in the same plane with the inner binary, its mass is calculated to be 4.7 (0.4) $M_{\odot}$ and the separation is 25.2(2.8) au.

If the third body is a normal star, it should contribute to the total light of the system. However, when we try to solve the light curves with third light l_3, the resulting l_3 is always negative or close to zero. This implies that the additional body is invisible in the optical. Both the large mass and the optical invisibility of the third body indicate that it may be a black hole. If this hypothesis is real, we cannot stop to image the formation of this multi-star system. By using single star evolution formulae (SSE; Hurley et al. 2000), the progenitor star of such a black hole is about 20 solar masses; before the supernova explosion, it might have lost mass up to 12 $M_\odot$ in an adiabatic situation. For adiabatic mass loss, the final and initial semimajor axis (SMA; af and a) have a simple relation: $af = m/mf \times a$, where m is initial mass of the star, and mf is the star's mass after the adiabatic expansion. The initial SMA could be estimated as about 15 au. However, this value is just an upper limit that may be changed in the other situations, such as if the supernova had a kick to it (e.g., Hamers et al. 2018). As for the central binary, the initial SMA may be much larger than the current SMA (about 8.0 $R_\odot$) because a system cannot stay so compact for a long time. By using the following relation for a system that stays stable for long timescale (see Naoz 2016),

$$\frac{a_1}{a_2}\frac{e_2}{1-e_2^2} < 0.1, \tag{7}$$

we could calculate that the $a_1 \times (e_2/(1-e_2^2))$ is shorter than 1.5 au by considering $a_2 = 15$ au. This indicates that the initial SMA of inner orbit could be very larger than the current value and the outer orbit had a much smaller initial SMA. More concern should be paid to the dynamical evolution of this triple system (Toonen et al. 2016). Recently, Naoz & Fabrycky (2014) investigated the secular evolution of triple stellar systems. They showed that the eccentric Kozai–Lidov (EKL) mechanism can produce a tidal tightening of inner binaries of triple stars, resulting in a merger event. By comparing the parameters of V593 Cen to their results, we find that the system is in agreement with one of the "merged" systems proposed by Naoz & Fabrycky (2014). There is also another limit that they can reach; this comes from the requirement that if Kozai–Lidov indeed caused the binary to become a contact binary, the general relativity (GR) precession rate should have been longer than the quadrupole timescale. By using the timescale relationship of the Kozai mechanism (Naoz 2016), the quadrupole timescale should be about 30 million years when the eccentricity of the outer orbit was taken as zero. From Equations (39)–(41) of Naoz et al. (2013), the GR precession rate could be estimated to be about 40 million years. The GR precession rate is longer that the quadrupole timescale, which implies that the Kozai mechanism could make the binary into a contact configuration. All of these estimations indicate that the additional body may speed the evolution of the inner binary and play an important role in the formation of the contact configuration through EKL.

This binary system with a black hole is similar to the B-type massive binary V Pup (Qian et al. 2008), where a black hole candidate with a mass no less than 10.4 $M_\odot$ was reported. The black hole candidate in V Pup may produce a weak X-ray source close to the binary by accreting materials from the massive binary via a stellar wind, while the interstellar matter with many heavy elements around this binary was caused by the supernova explosion of the black hole progenitor. A recent investigation by Matsumoto et al. (2018) has shown that X-ray novae could be produced by isolated single black holes accreting from interstellar matter. As for V593 Cen, new observations in optical and X-ray wavelengths are needed. Moreover, if the cyclic oscillation is caused by the presence of a black hole, it should show a strictly periodic change. However, as we can see in Figure 2, the data do not cover the whole cycle of the $O-C$ diagram. To confirm this periodic oscillation, more eclipse times of the binary are required in the future.

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References

Applegate, J. H. 1992, ApJ, 385, 621
Bell, S. A., & Malcolm, G. J. 1987, MNRAS, 226, 899
Borkovits, T., & Hegedüs, T. 1996, A&AS, 120, 63
Chambliss, C. R. 1992, PASP, 104, 663
Cox, A. N. 2000, Allens Astrophysical Quantities (4th ed.; New York: AIP Press; Springer)
Dvorak, S. W. 2004, IBVS, 5542, 1
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
Hamers, A. S., Cai, M. X., Roa, J., & Leigh, N. 2018, MNRAS, 480, 3800
Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, MNRAS, 315, 543
Irwin, J. B. 1952, ApJ, 116, 211
Lanza, A. F., Rodonò, M., & Rosner, R. 1998, MNRAS, 296, 893
Lapasset, E., Claria, J. J., & Gomez, M. 1988, IBVS, 3161, 1
Lapasset, E., Gómez, M., & Clari, J. J. 1987a, BAAA, 33, 301
Lapasset, E., Gómez, M. N., & Claria, J. J. 1987b, RMxAA, 14, 402
Liao, W.-P., & Qian, S.-B. 2010, MNRAS, 405, 1930
Lucy, L. B. 1967, ZA, 65, 89
Lyngå, G. 1970, IAUS, 38, 270
Matsumoto, T., Teraki, Y., & Ioka, K. 2018, MNRAS, 475, 1251
Moe, M., & Di Stefano, R. 2017, ApJS, 230, 15
Naoz, S. 2016, ARA&A, 54, 441
Naoz, S., & Fabrycky, D. C. 2014, ApJ, 793, 137
Naoz, S., Kocsis, B., Loeb, A., & Yunes, N. 2013, ApJ, 773, 187
Plewa, T., & Wlodarczyk, K. J. 1993, AcA, 43, 249
Pojmanski, G., & Maciejewski, G. 2004, AcA, 54, 153
Qian, S.-B., He, J.-J., Zhang, J., et al. 2017, RAA, 17, 87
Qian, S.-B., Liao, W.-P., & Fernández Lajús, E. 2008, ApJ, 687, 466
Qian, S.-B., Liu, L., & Kreiner, J. M. 2006, NewA, 12, 117
Qian, S.-B., Yuan, J.-Z., Liu, L., et al. 2007, MNRAS, 380, 1599
Qian, S.-B., Zhang, J., Wang, J.-J., et al. 2013, ApJs, 207, 22
Raghavan, D., McAlister, H. A., Henry, T. J., et al. 2010, ApJS, 190, 1
Rucinski, S. M. 1969, AcA, 19, 245
Shapley, H., & Swope, H. H. 1940, AnHar, 90, 177
Shatsky, N. 2001, A&A, 380, 238
Tokovinin, A. A. 1997, A&AS, 124, 75
Tokovinin, A. A. 2004, RMxAC, 21, 7
Tokovinin, A. A. 2008, MNRAS, 389, 925
Toonen, S., Hamers, A., & Portegies Zwart, S. 2016, ComAC, 3, 6
Van Gent, H. 1948, BAN, 10, 382
Van Hamme, W., & Wilson, R. E. 2003, in ASP Conf. Ser. 298, GAIA Spectroscopy, Science and Technology, ed. U. Munari (San Francisco, CA: ASP), 323
Wilson, R. E. 1990, ApJ, 356, 613
Wilson, R. E. 1994, PASP, 106, 921
Wilson, R. E. 2012, AJ, 144, 73
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Zhao, E.-G., Qian, S.-B., Fernández Lajús, E., von Essen, C., & Zhu, L.-Y. 2010, RAA, 10, 438
Zhao, E.-G., Qian, S.-B., Li, L., et al. 2018a, PASP, 130, 084205
Zhao, E.-G., Qian, S.-B., Zejda, M., Zhang, B., & Zhang, J. 2018b, RAA, 18, 59