A cyclical period variation detected in the updated orbital period analysis of TV Columbae

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November 6, 2018

Abstract

The two CCD photometries of the intermediate polar TV Columbae are made for obtaining the two updated eclipse timings with high precision. There is an interval time $\sim 17yr$ since the last mid-eclipse time observed in 1991. Thus, the new mid-eclipse times can offer an opportunity to check the previous orbital ephemerides. A calculation indicates that the orbital ephemeris derived by Augusteijn et al. (1994) should be corrected. Based on the proper linear ephemeris (Hellier , 1993), the new orbital period analysis suggests a cyclical period variation in the O-C diagram of TV Columbae. Using Applegate's mechanism to explain the periodic oscillation in O-C diagram, the required energy is larger than that a M0-type star can afford over a complete variation period $\sim 31.0(\pm 3.0)yr$. Thus, the light travel-time effect indicates that the tertiary component in TV Columbae may be a dwarf with a low mass, which is near the mass lower limit $\sim 0.08M_\odot$ as long as the inclination of the third body high enough.

Stars: cataclysmic variables; Stars : binaries : eclipsing; Stars : individual (TV Columbae)

1 Introduction

An intermediate polar TV Columbae was first discovered as a hard X-ray source 2A 0526-328 by Cooke et al. (1978). The subsequent photometries and spectroscopies detected five periods of 32 min, 5.2 hr, 5.5 hr, 6.3 hr and ~4 day, which corresponding to the spin modulation in X-ray (Schrijver et al. , 1985), the beat period between 5.5 hr and 4 day (Motch , 1981), the binary orbital period (Hutchings et al. , 1981), the permanent positive superhump period (Retter et al. , 2003) and the nodal precession of the accretion disc period (Hellier ,

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1993), respectively. No until Hellier et al. (1991) was the eclipse in TV Columbae reported. Except for the 32 min detected in X-ray observation, the other four periods presented in optical regime give rise to the high variabilities in eclipse light curves of TV Columbae (Hellier et al. , 1991; Hellier , 1993; Augusteijn et al. , 1994). Although the eclipse light curves of TV Columbae show cycle-to-cycle variations, a shallow eclipse of part of the accretion disc is established. Hellier (1993) and Augusteijn et al. (1994) have pointed out that the eclipse of TV Columbae in a certain case (maybe outburst) is clearly modulated by a broader quasi-sinusoidal modulation. Moreover, Hellier (1993) found a peculiar phenomenon in TV Columbae that its eclipse can totally disappear in the light curve observed in January 1st, 1986.

Since plenty of investigators focused on the variations of 5.2 hr and 4 day periods, few analyses in its orbital period were made in the past. However, many 5.2 hr period analyses indicate that this period is not stable and can change non-monotonically with time (Augusteijn et al. , 1994). In addition, it is difficult to detect the variations of 4-d modulation because of the short observation time in most case. Thus, the stable and distinct photometric period of 5.5 hr in TV Columbae can provide a best opportunity to probe the possible evolutional state and inner interaction between two components. The first orbital period analysis (Hellier , 1993) suggested that the quadratic term in the O-C diagram was suspected. Then Augusteijn et al. (1994) and Rana et al. (2004) never detected the changes in its orbital period. A time span of about 17 years, from the last eclipse timing (Hellier , 1993) to now, implies that an updated and available orbital period analysis is expected to detect the possible variations in orbital period of TV Columbae.

In this paper, the two light curves near the mid-eclipse by CCD photometries and two new eclipse timings of TV Columbae with high precision are presented in Sect. 2. Then Sect. 3 deals with the details of the updated O-C analysis in the orbital period of 5.5 hr. Finally, the probable discussions for the observed orbital period changes are made in Sect. 4 and our principal conclusions in Sect. 5.

2 Observations

Two new times of light minimum are obtained from our CCD photometric observations with the VersArray 1300B CCD camera attached to the 2.15-m Jorge Sahade telescope at Complejo Astronomico El Leoncito (CASLEO), San Juan, Argentina. Both photometries of TV Columbae in V-filter were carried out on November 18 and 20, 2009. Two nearby stars which have the similar brightness in the same viewing field of telescope are chosen as the comparison star and the check star, respectively. All images were reduced by using PHOT (measure magnitudes for a list of stars) of the aperture photometry package of IRAF.

Two partial eclipse light curves shown in Fig. 1 indicate obviously night-to-night variations, which present different eclipse depth ($0^m.2 \sim 0^m.45$) at the different cycle. A nearly flat-toped maximum with a phase range $0.6 \sim 0.9$ is detected in the eclipse light curve observed in November 18, 2009, which is never found in the

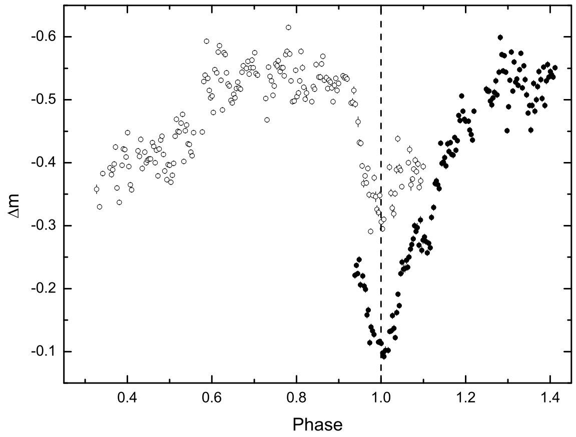

Figure 1: The eclipse parts of light curves of intermediate polar TV Columbae in V-filter measured on 2009 November 18 and 20 by using 2.15-m Jorge Sahade telescope at CASLEO, are plotted in open and solid circles, respectively. The dash line indicates the mid-eclipse.

previous photometries (Hellier et al. , 1991; Hellier , 1993; Augusteijn et al. , 1994). Moreover, we obtained a distinct eclipse profile with a long egress in the other observation in November 20, 2009. The orbital light curves of TV Columbae in outburst are similar as the sinusoidal curves (see the photometries in 1987, 1988 and 1991 outbursts), which are totally different with those observed in quiescence. Thus, considering the extreme changes in the eclipse profiles at different epochs, the eclipse timings with high precision are important for the investigation of variations in orbital period of TV Columbae. Two accurate times of mid-eclipse were derived by using a parabolic fitting method to the very deepest part of the eclipse. Including the previous 43 times of light minimum for TV Columbae (Hellier et al. , 1991; Hellier , 1993; Augusteijn et al. , 1994), we listed all 45 available times of light minimum covering near 30 yr in Table 1.

3 Analysis of orbital period change

The data from AAVSO an International Database (http://www.aavso.org/data/download/) suggest that TV Columbae is not in outburst during our observations, and from Fig. 1 it cannot be seen that a dip around orbital phase $\sim$ 1.2, which is different from the light curves in 1987 I and 1988 obtained by Augusteijn et al. (1994). A recent orbital ephemeris (Augusteijn et al. , 1994; Rana et al. , 2004),

$$T_{min} = HJD\ 2447151.2324(11) + 0^{d}.22859884(77)E, \tag{1}$$

is used to check whether the updated two eclipse timings obey the regular 5.5 hr orbital modulation. The two cycles 35007.226 and 35015.214 corresponding to the observed mid-eclipse times HJD 2455153.843579(76) and HJD 2455155.669797(71), respectively, are calculated, which means that both observed orbital eclipse

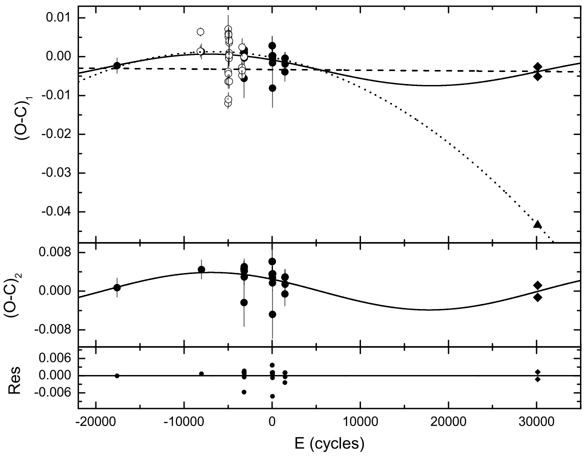

Figure 2: The $(O-C)_1$ values of TV Columbae are calculated by Eq. 2. The best fit linear and sinusoidal curves are plotted by dash line and solid line, respectively. The two $(O-C)_1$ values at the same cycles as our data points, which are predicted by the quadratic ephemeris (Hellier , 1993) denoted by the dotted line, are plotted by the solid upper triangles. The open circles represent the data points from Augusteijn et al. (1994), the filled diamonds and circles the two data points we obtained and the data from the other papers, respectively. After removing the linear element from the $(O-C)_1$ diagram and the data from Augusteijn et al. (1994), the $(O-C)_2$ values shown in the middle panel suggest a significant cyclical period change. The residuals and their linear fitted solid line are presented in the bottom panel. The ordinates of all three panels are in day units.

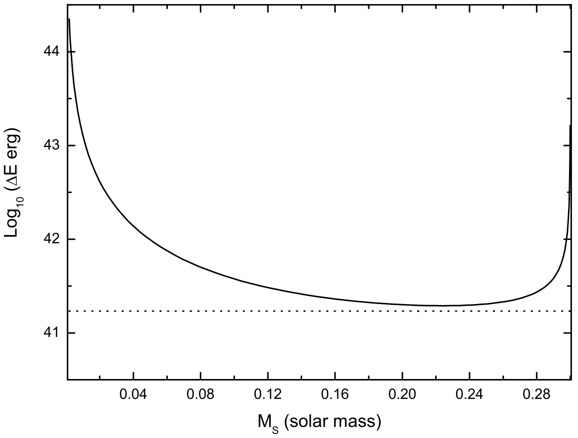

Figure 3: The solid line denotes the energy required by Applegate's mechanism corresponding to the different shell mass. The dash line refers to the total radiant energy of a M0-type star over the whole oscillation period $\sim 31yr$.

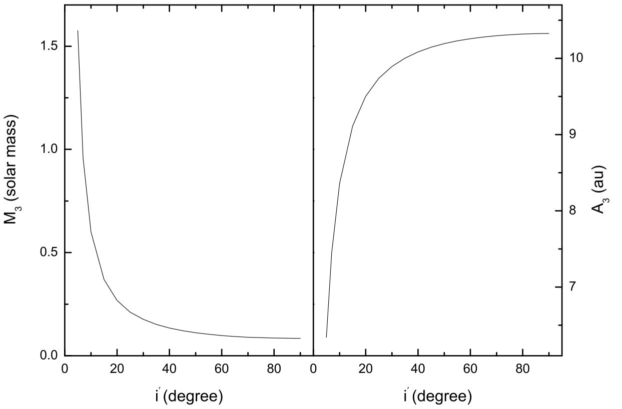

Figure 4: The masses and separations of the tertiary component in TV Columbae vs. its orbital inclination i' are plotted in the left and right panels, respectively.

minima are about 0.2 in phase later than the predicted times. This large discrepancy implies that TV Columbae should seriously expand its orbit in an extreme short timescale ($\sim 30yr$), which is obviously not supported by observations. This means that either the two derived eclipse timings or the orbital ephemeris Eq. 1 are wrong. However, the orbital ephemeris derived by Hellier (1993),

$$T_{min} = HJD\ 2448267.4895(7) + 0^{d}.22860034(16)E, \quad (2)$$

can accurately predict the mid-eclipse times are HJD 2455153.846142 and HJD 2455155.674945, which corresponds to the O-C values $-0^{d}.0026$ and $-0^{d}.0051$, respectively. Therefore, although both light curves we obtained are not complete and the multi-periodic modulations badly affect the profiles of orbital light curves, we can ensure that the derived mid-eclipse times are correct. In order to find the error in Eq. 1, we carefully compared both ephemerides, and then found that the small discrepancy $\sim 1^{d}.5 \times 10^{-6}$ in the average orbital period between Eq. 1 and Eq. 2 is accumulated to $\sim 0^{d}.053$ (i.e. ~ 0.2 in phase) over 30 years. Moreover, the error in average orbital period may explain the deviations and phase shifts of eclipse times in Augusteijn et al. (1994).

The O-C values of 45 eclipse timings for TV Columbae listed in column 6 of Table 1 are calculated by using Eq. 2. The new O-C diagram shown in Fig. 2 suggests a possible cyclical variation instead of the secular decrease derived by Hellier (1993), because Hellier's quadratic ephemeris predicted the O-C values at the same cycles as our data are about $-0^{d}.0434$ shown in the upper panel of Fig. 2, which are clearly distinct with our observations. Therefore,we attempted to use a linear-plus-sinusoidal ephemeris to fit the O-C values. Since the large scatters from ~ -10000 cycles to ~ 0 cycles obviously exceed the errors of the mid-eclipse times, the probable weights should be reconsidered instead of those calculated from the uncertainties of the mid-eclipse times. The incorrect orbital ephemeris and the possible deviations in eclipse times derived by Augusteijn et al. (1994) imply that the weights of their data should be lower than the others. Therefore, a least-square solution for the O-C values of TV Columbae leads to

$$\begin{aligned}(O-C)_1 = & -3^d.32(\pm0^d.07)\times10^{-3} - 1^d.63(\pm0^d.28)\times10^{-8}E \\ & + 3^d.87(\pm0^d.09)\times10^{-3}\sin[0^\circ.0073(\pm0^\circ.0007)E + 140^\circ.4(\pm1^\circ.2)].\end{aligned} \tag{3}$$

Although the early data present large scatters, all the high-precision data except for the two data points with large error bars $0^d.005$ (Hellier , 1993) well support a possible cyclical variation trend in O-C diagram after removing the data from Augusteijn et al. (1994) and the linear element, which is clearly shown in the middle panel of Fig. 2. Moreover, the fitting $\chi^2 \sim 1.2$ suggests that a cyclical period variation with a period of $31.0(\pm3.0)yr$ is significant.

4 Discussion

The radial velocity measurements (Hutchings et al. , 1981; Hellier , 1993) and the spectroscopic analyses (Vrtilek et al. , 1996; Cropper et al. , 1999; Ishida & Ezuka , 1999; Ramsey , 2000) never obtained the consistent system parameters of TV Columbae. According to the classification of TV Columbae as a permanent superhump system (Retter et al. , 2003), TV Columbae may be an extreme system with a mass ratio ~ 0.3, which is in contradiction with that calculated by the relation between the orbital period and the secondary mass in CVs (Smith & Dhillon , 1998). Moreover, assuming that the white dwarf in TV Columbae has a typical mass of $\sim 1M_\odot$, the secondary mass can be estimated to be $\sim 0.3M_\odot$, which may be agree with the estimated spectra type of the secondary late K or early M type (Beuermann , 2000; Smith & Dhillon , 1998). Thus, we adopted a combined mass of $1M_\odot + 0.3M_\odot$ for the eclipsing pair of TV Columbae.

Considering that the eclipse of the intermediate polar TV Columbae may be of a partial accretion disc caused by the magnetic of the white dwarf, the changes in the partial disc may produce the changes in the O-C diagram shown in Fig. 2. Moreover, a cyclical period variation can be interpreted by two plausible mechanisms, which are Applegate's mechanism (Applegate , 1992) and light travel-time effect. As for the former, a careful calculation for the variation of quadrupole momentum suggests that $\triangle Q = -2.03(\pm0.05)\times10^{48} g\ cm^2$. Considering the secondary in TV Columbae is known little, the energies required to cause the observed O-C oscillation corresponding to different assumed shell masses are calculated. The lowest required energy $\triangle E_{min} \sim 1.9\times10^{41} erg$ at $M_s \simeq 0.22M_\odot$, is larger than the total radiant energy of a M0 type star over a complete variation period $\sim 31yr$, $E_0 \sim 1.7\times10^{41} erg$. Therefore, a solar-type magnetic cycle may have difficulty explaining the observed cyclical period variation in TV Columbae as the previous analysis for other CVs (Dai et al. , 2009; Dai & Qian , 2010).

Another plausible mechanism for explaining the cyclical period variation in O-C diagram is the light travel-time effect caused by a perturbations from a tertiary component. If the two data points at cycles -3193 and 26 with large error bars can be omitted, then the cyclical period changes shown in the middle panel of Fig. 2 would well support an excellent sinusoidal fit. By using the amplitude of sinusoidal curve and the Third Kepler Law, the projected distance $a' \sin(i')$ from binary to the mass center of the triple system and the mass function of the third component $f(m_3)$ can be calculated to be $0.67(\pm0.02)au$ and $3.1(\pm0.2)\times10^{-4}M_\odot$, respectively. According to the both relationships described in Fig. 4, the mass of the third star in TV Columbae is very close to the mass lower limit of a star with stable hydrogen burning ($\sim 0.08M_\odot$) when the inclination of the third star is higher enough. In addition, the distance from the third body to the mass center of system is $\sim 10.3au$, which is over two orders of magnitude larger than the separation of binary. Thus, this third star can survive the previous common envelope evolution of the parent binary.

5 Conclusion

Two new light curves near mid-eclipse with obviously night-to-night variations are obtained. Moreover, a near flat-top shape maximum in the light curve observed in November 18, 2009 with a phase range 0.6 ~ 0.9 is first detected. Both updated eclipse timings with high precision for intermediate polar TV Columbae we observed, which indicate a phase shift of ~ 0.2 by using Eq. 1, can be accurately predicted by Eq. 2. A compare between the two orbital ephemerides indicates that the average orbital period derived by Augusteijn et al. (1994) is incorrect and the errors are accumulated to $\sim 0^d.053$ (i.e. ~ 0.2 in phase) over the 30 years. This means the Augusteijn's orbital ephemeris is not appropriate for calculating the orbital phase of TV Columbae. Based on the probable linear ephemeris, a detailed orbital period analysis suggests a significant cyclical period variation with a period of $31.0(\pm3.0)yr$ in its O-C diagram, which can not be explained by Applegate's mechanism. Accordingly, a light travel-time effect is applied to interpret the cyclical period change. The third body in TV Columbae may be a low mass dwarf as long as the orbital inclination of tertiary component high enough. Since TV Columbae is a complex system and the explanations for its updated O-C diagram is only based on the two new mid-eclipse timings, the cyclical period change shown in Fig. 2 should be checked by the more data in the future. Although the system parameters of TV Columbae are ambiguous, which means that any conclusive result cannot be obtained, the discussions based on some plausible assumptions are still important to the further understanding for TV Columbae. Therefore, the more observations including CCD photometries with a longer base line and spectroscopies with high resolution are needed to probe such multi-periodic system.

Acknowledgements

This work was partly Supported by Special Foundation of President of The Chinese Academy of Sciences and West Light Foundation of The Chinese Academy of Sciences, Yunnan Natural Science Foundation (2008CD157), the Yunnan Natural Science Foundation (No. 2005A0059M) and Chinese Natural Science Foundation (No.10573032, No. 10573013 and No.10433030). CCD photometric observations of TV Columbae were obtained with the 2.15-m Jorge Sahade telescope at CASLEO, San Juan, Argentina. We thank the referee very much for the helpful comments and suggestions that helped to improve this paper greatly.

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Table 1: The 45 eclipse timings for the intermediate polar TV Columbae.

JD.Hel. 2400000+	type	error	Method	E (cycle)	$(O-C)^d_1$	Ref.
44243.664000	pri	.002	pe	-17602	-.0023	(1)
46403.712300	pri	.0015	pe	-8153	.0014	(2)
46409.660900	pri	.0011	pe	-8127	.0064	(2)
46431.372900	pri	.002	ccd	-8032	.0013	(3)
47122.647200	pri	.0014	pe	-5008	-.012	(2)
47124.712600	pri	.0036	pe	-4999	-.0038	(2)
47125.627000	pri	.0015	pe	-4995	-.0038	(2)
47126.767400	pri	.0018	pe	-4990	-.0064	(2)
47127.695300	pri	.0036	pe	-4986	.0071	(2)
47128.607700	pri	.0019	pe	-4982	.0051	(2)
47129.734400	pri	.0018	pe	-4977	-.011	(2)
47130.655600	pri	.0009	pe	-4973	-.0044	(2)
47131.808900	pri	.0015	pe	-4968	.0059	(2)
47134.780500	pri	.002	pe	-4955	.0057	(2)
47146.661800	pri	.002	pe	-4903	-.00023	(2)
47147.804600	pri	.0021	pe	-4898	-.00043	(2)
47148.723000	pri	.0032	pe	-4894	.0036	(2)
47150.777800	pri	.002	pe	-4885	.00096	(2)
47151.691600	pri	.0022	pe	-4881	.00036	(2)
47153.742200	pri	.0018	pe	-4872	-.0064	(2)
47155.581500	pri	.0021	pe	-4864	.0041	(2)
47481.785300	pri	.0013	pe	-3437	-.0048	(2)
47482.701700	pri	.002	pe	-3433	-.0028	(2)
47486.815700	pri	.0021	pe	-3415	-.0036	(2)
47487.736100	pri	.0023	pe	-3411	.0024	(2)
47537.111400	pri	.0016	ccd	-3195	-.000014	(4)
47537.563000	pri	.005	ccd	-3193	-.0056	(3)
47538.484400	pri	.0016	ccd	-3189	.0014	(3)
47539.398700	pri	.0016	ccd	-3185	.0013	(3)
47540.540100	pri	.0016	ccd	-3180	-.00032	(3)
47541.456600	pri	.0016	ccd	-3176	.0018	(3)
47542.370100	pri	.0016	ccd	-3172	.00088	(3)
48266.349300	pri	.0025	ccd	-5	.0028	(3)
48267.489700	pri	.0016	ccd	0	.0002	(3)
48268.406700	pri	.0025	ccd	4	.0028	(3)
48273.425000	pri	.005	ccd	26	-.0081	(3)

Table 1: Continued.

JD.Hel. 2400000+	type	error	Method	E (cycle)	$(O-C)^d_1$	Ref.
48274.345900	pri	.0016	ccd	30	-.0016	(3)
48275.490000	pri	.0016	ccd	35	-.00051	(3)
48278.462600	pri	.0016	ccd	48	.00028	(3)
48595.301900	pri	.0016	ccd	1434	-.00049	(3)
48599.413300	pri	.0025	ccd	1452	-.0039	(3)
48602.388600	pri	.0016	ccd	1465	-.0004	(3)
48603.530100	pri	.0025	ccd	1470	-.0019	(3)
55153.843579	pri	.000076	ccd	30124	-.0026	(5)
55155.669797	pri	.000071	ccd	30132	-.0051	(5)

References: (1) Motch (1981); (2) Augusteijn et al. (1994); (3) Hellier (1993); (4) Hellier et al. (1991); (5) This paper.