Research in Astron. Astrophys. **2009** Vol. **9** No. **3**, 307–314
*http://www.raa-journal.org* *http://www.iop.org/journals/raa*

***R**esearch in*
***A**stronomy and*
***A**strophysics*

# An orbital period investigation of the Algol-type eclipsing binary VW Hydrae *

Jia Zhang[1,2], Sheng-Bang Qian[1] and Boonrucksar Soonthornthum[3]

[1] National Astronomical Observatories/Yunnan Observatory, Chinese Academy of Sciences, Kunming 650011, China; *yelangdadi@163.com*
[2] Graduate School of the Chinese Academy of Sciences, Beijing 100039, China
[3] National Astronomical Research Institute of Thailand/Ministry of Science and Technology, Bangkok, Thailand

Received 2008 May 8; accepted 2008 July 4

**Abstract** Orbital period variations of the Algol-type eclipsing binary, VW Hydrae, are analyzed based on one newly determined eclipse time and the other times of light minima collected from the literature. It is discovered that the orbital period shows a continuous increase at a rate of $dP/dt = +6.34\times10^{-7}$ d yr$^{-1}$ while it undergoes a cyclic change with an amplitude of 0.0639 d and a period of 51.5 yr. After the long-term period increase and the large-amplitude period oscillation were subtracted from the O-C curve, the residuals of the photoelectric and CCD data indicate a small-amplitude cyclic variation with a period of 8.75 yr and a small amplitude of 0.0048 d. The continuous period increase indicates a conservative mass transfer at a rate of $dM_2/dt = 7.89 \times 10^{-8}\,M_\odot$ yr$^{-1}$ from the secondary to the primary. The period increase may be caused by a combination of the mass transfer from the secondary to the primary and the angular momentum transfer from the binary system to the circumbinary disk. The two cyclic period oscillations can be explained by light-travel time effects via the presence of additional bodies. The small-amplitude periodic change indicates the existence of a less massive component with mass $M_3 > 0.53\,M_\odot$, while the large-amplitude one is caused by the presence of a more massive component with mass $M_4 > 2.84\,M_\odot$. The ultraviolet source in the system reported by Kviz & Rufener (1987) may be one of the additional components, and it is possible that the more massive one may be an unseen neutron star or black hole. The rapid period increase and the possibility of the presence of two additional components in the binary make it a very interesting system to study. New photometric and high-resolution spectroscopic observations and a detailed investigation of those data are required in the future.

**Key words:** stars: binaries: close — stars: binaries: eclipsing — multiple stars — stars: individual (VW Hya)

## 1 INTRODUCTION

VW Hydrae was discovered to be an eclipsing binary by Hoffmeister (1929). It shows a very deep minimum with a maximum brightness of 10.5 mag. Kviz & Rufener (1987) published photoelectric

* Supported by the National Natural Science Foundation of China.

observations in $UBV$ bands and derived a new linear ephemeris,

$$\mathrm{Min}.I = 2446083.7665 + 2^{\mathrm{d}}.6964378 \times E. \qquad (1)$$

They unexpectedly found a secondary which was too deep in the $U$-band and argued that there is an ultraviolet source in the system that must be eclipsed during the secondary eclipse. The first radial velocity curves for both components and the complete light curves in multiple bands were published by Burki et al. (2005). Their light curves were analyzed with the Wilson-Devinney method (Wilson & Devinney 1971; Wilson 1994), and absolute parameters of the binary were determined. The spectral types of both components were classified by Burki et al. (2005) as B8/9V (the primary) and F9III (the secondary). In the present paper, the mass transfer, the interaction between the circumbinary disk and the central binary system, and the light-travel time effects, are all investigated based on the analysis of the period changes of the Algol-type eclipsing binary.

## 2 NEW CCD PHOTOMETRIC OBSERVATIONS FOR VW HYDRAE

CCD photometric observations of the Algol-type eclipsing binary VW Hydrae were carried out on 2007 March 5 with the PI1024 TKB CCD photometric system attached to the 1.0-m reflecting telescope at the Yunnan Observatory. During the observation, the R filter, which was used, is close to the standard Johnson UBVRI system. The integration time for each image was 30 s. The coordinates of the variable star, the comparison star and the check star are listed in Table 1. Those observed images were reduced with PHOT (which measure magnitudes for a list of stars) of the aperture photometry package of IRAF. Using our photometric data, the time of light minimum, HJD $2454165.1450(\pm 0.0002)$, was determined using a parabolic fitting method. The photometric observations are displayed in Figure 1. As shown in this figure, the light variation around the primary minimum is continuous, which indicates a partial eclipse like that reported by Burki et al. (2005).

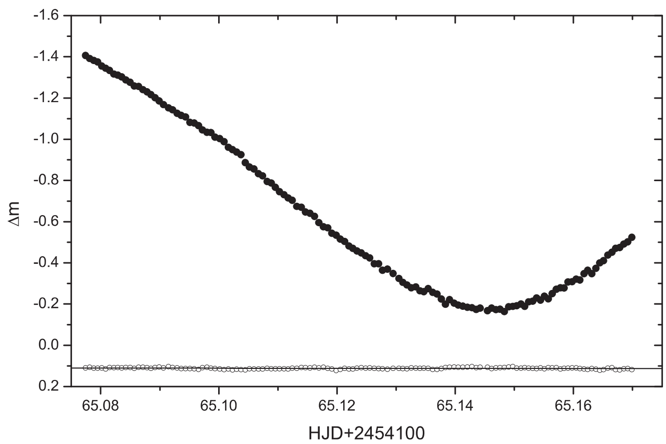


**Fig. 1** CCD photometric observations of VW Hydrae in the $R$-band obtained on 2007 March 5. Solid dots refer to the magnitude differences between the VW Hydrae and the comparison star and open circles to those between that comparison and the check stars.

## 3 ORBITAL PERIOD VARIATION OF VW HYDRAE

Orbital period variation of VW Hydrae was recently analyzed by Burki et al. (2005) who suggested a period increase and probable sudden changes that are superimposed on the period increase. However, the data they used were not complete. To understand the properties of the period change, we compiled

**Table 1** Coordinates of VW Hydrae, the Comparison and the Check Star

| Stars | $\alpha_{2000}$ | $\delta_{2000}$ |
|---|---|---|
| VW Hydrae | $08^{\mathrm{h}}33^{\mathrm{m}}51.0^{\mathrm{s}}$ | $-14°39'53.9''$ |
| The comparison | $08^{\mathrm{h}}33^{\mathrm{m}}53.2^{\mathrm{s}}$ | $-14°41'02.4''$ |
| The check | $08^{\mathrm{h}}33^{\mathrm{m}}55.0^{\mathrm{s}}$ | $-14°42'30.4''$ |

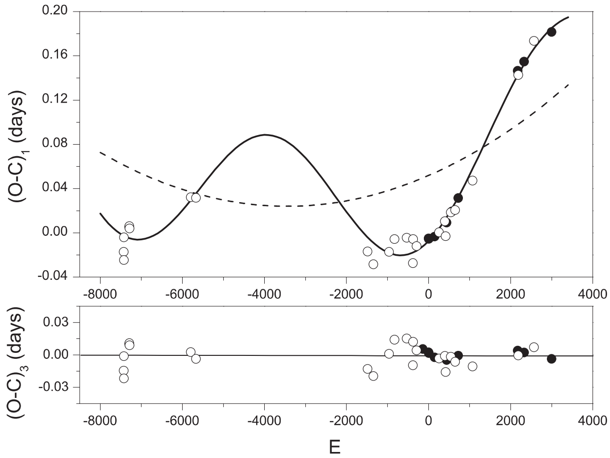


**Fig. 2** $O-C$ diagrams of the Algol-type eclipsing binary star VW Hydrae based on all the available times of light minima. Open circles refer to photographic or visual observations and solid dots to photoelectric or CCD data. The dashed line refers to a long-term period increase and the solid line represents a combination of the continuous increase and a cyclic period variation. The residuals from the whole effect are displayed in the lower panel.

all the available times of the light minima. The eclipse times are mainly collected from Kreiner et al. (2001) and Burki et al. (2005). Meanwhile, some available eclipse times were compiled by Kreiner and were kindly provided to us. All the data are listed in Table 2, where 'v', 'e' and 'ccd' refer to visual, photoelectric and CCD observations, respectively. The total primary eclipse of VW Hydrae is 3.2 mag deep in the $V$-band (Burki et al. 2005). For its very deep eclipse, the visual times of light minima of VW Hydrae are precise enough (less than 0.01 d) for $(O-C)$ analysis.

The $(O-C)_1$ values were computed with the ephemeris given by Kreiner et al. (2001),

$$\mathrm{Min}.I = 2446083.7714 + 2^{\mathrm{d}}.6964271 \times E. \tag{2}$$

The corresponding $(O-C)_1$ curve is shown in the upper panel of Figure 2 where solid dots refer to photoelectric and CCD observations and open circles to visual observations. There are only 35 points in the figure, but the period of time covered by the points is about 80 yr, so the long time variation of VW Hydrae can be worked out through these observations. There are two gaps in the $(O-C)_1$ curve that can not be filled; we can only analyze all available data and provide a possible explanation. More precise observations are needed for a more reliable analysis.

The $(O-C)_1$ diagram displayed in Figure 2 suggests that the period variation of VW Hydrae is very complex. We consider a combination of a cyclic variation and a long-term period increase. A weighted least-squares solution which weights 8 to photoelectric or CCD data and 1 to visual data yields the following equation,

$$\begin{aligned}\mathrm{Min}.I = {} & 2446083.8232(\pm 0.0039) + 2.^{\mathrm{d}}69644325(\pm 0.00000238) \times E \\ & +2.34(\pm 0.33) \times 10^{-9} \times E^2 \\ & +0.0639(\pm 0.0048)\sin[0.0258° \times E + 292.2°(\pm 2.9°)].\end{aligned} \tag{3}$$

**Table 2** Times of Light Minima of VW Hydrae

| JD.Hel. | Method | E | $(O-C)_1$ | Weight | Reference |
|---|---|---|---|---|---|
| 2426057.390 | v | –7427 | –0.0173 | 0.1 | (1) |
| 2426065.472 | v | –7424 | –0.0246 | 0.1 | (1) |
| 2426068.189 | v | –7423 | –0.0040 | 0.1 | (1) |
| 2426413.341 | v | –7295 | 0.0053 | 0.1 | (1) |
| 2426421.430 | v | –7292 | 0.0050 | 0.1 | (2) |
| 2426421.431 | v | –7292 | 0.0060 | 0.1 | (1) |
| 2426440.304 | v | –7285 | 0.0040 | 0.1 | (1) |
| 2430455.312 | v | –5796 | 0.0321 | 0.1 | (3) |
| 2430792.365 | v | –5671 | 0.0317 | 0.1 | (3) |
| 2442071.471 | v | –1488 | –0.0169 | 0.1 | (4) |
| 2442454.352 | v | –1346 | –0.0285 | 0.1 | (5) |
| 2443481.702 | v | –965 | –0.0172 | 0.1 | (6) |
| 2443837.642 | v | –833 | –0.0056 | 0.1 | (7) |
| 2444638.482 | v | –536 | –0.0045 | 0.1 | (8) |
| 2445048.316 | v | –384 | –0.0274 | 0.1 | (9) |
| 2445056.427 | v | –381 | –0.0057 | 0.1 | (9) |
| 2445285.617 | v | –296 | –0.0120 | 0.1 | (10) |
| 2445695.4791 | ccd | –144 | -0.0068 | 0.8 | (11) |
| 2446083.7665 | e | 0 | –0.0049 | 0.8 | (12) |
| 2446086.4623 | ccd | 1 | –0.0055 | 0.8 | (11) |
| 2446480.1428 | ccd | 147 | –0.0034 | 0.8 | (11) |
| 2446760.575 | v | 251 | 0.0004 | 0.1 | (13) |
| 2447151.567 | v | 196 | 0.0105 | 0.1 | (14) |
| 2447205.482 | v | 416 | –0.0031 | 0.1 | (15) |
| 2447262.1192 | ccd | 437 | 0.0092 | 0.8 | (11) |
| 2447542.557 | v | 541 | 0.0185 | 0.1 | (16) |
| 2447615.3614 | ccd | 568 | 0.0194 | 0.8 | (11) |
| 2447825.684 | v | 646 | 0.0207 | 0.1 | (17) |
| 2448025.2304 | ccd | 720 | 0.0315 | 0.8 | (11) |
| 2448971.692 | v | 1071 | 0.0472 | 0.1 | (18) |
| 2451937.8611 | ccd | 2171 | 0.1465 | 0.8 | (19) |
| 2451967.518 | v | 2182 | 0.1427 | 0.1 | (20) |
| 2452353.1192 | ccd | 2325 | 0.1548 | 0.8 | (21) |
| 2452997.584 | v | 2564 | 0.1735 | 0.1 | (22) |
| 2454165.1450 | ccd | 2997 | 0.1816 | 0.8 | (23) |

Reference: (1) Pagaczewski (1934); (2) Pagaczewski (1931); (3) Pagaczewski (1945); (4) Locher (1974); (5) Locher (1975); (6) Locher (1978a); (7) Locher (1978b); (8) Locher (1981); (9) Locher (1982); (10) Locher (1983); (11) Burki (private communication); (12) Kvizet et al. (1987); (13) Locher (1987); (14) Locher (1988a); (15) Locher (1988b); (16) Locher (1989); (17) Locher (1990); (18) Locher (1992); (19) Catonet & Smith (2005); (20) Locher (2001); (21) Nagai (2003); (22) Diethelm (2004); (23) This paper.

The general trend of the $(O-C)_1$ curve shows an upward parabolic change (dashed line in Fig. 2) indicating that the period is continuously increasing. With the quadratic term in Equation (3), the rate of the period increase is determined to be $dP/dt = +6.34(\pm 0.89) \times 10^{-7}$ d yr$^{-1}$, which corresponds to a period increase of 5.48 seconds per century. The derived period increase rate is smaller than that derived by Burki et al. (2005). The $(O-C)_3$ residuals corresponding to Equation (3) are plotted in the lower panel of Figure 2. The sinusoidal term indicates a cyclic variation with an amplitude of 0.0639 d and a period of 51.5 yr, which is more clearly seen in Figure 3 where the $(O-C)_2$ values based on the quadratic ephemeris in Equation (3) are displayed.

The error of the visual data is less than 0.01 d while that of the CCD and photoelectric data is less than 0.001 d, so we can use ccd and photoelectric data for a more detailed analysis. The $(O-C)_3$ values of all photoelectric and CCD times of light minima are plotted in the upper panel of Figure 4. It is shown in the panel that the scatter of the data points is up to 0.005 d, which is much larger than the error in this kind of data. This indicates that there may exist a small amplitude period oscillation. A least-squares

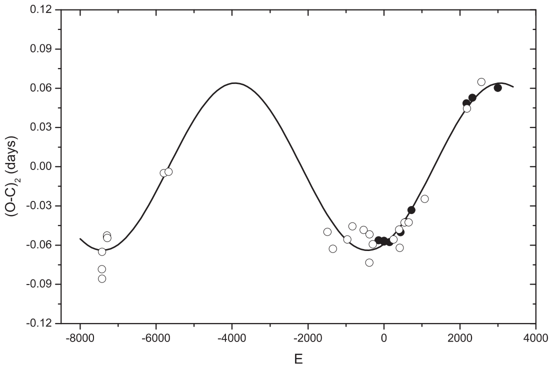


**Fig. 3** $(O-C)_2$ diagram of VW Hydrae computed with the quadratic ephemeris in Eq. (3). The solid line refers to the cyclic term in Eq. (3). Symbols are the same as those in Fig. 2.

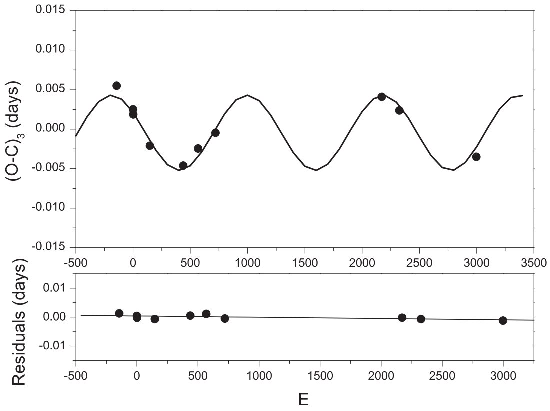


**Fig. 4** $(O-C)_3$ curve of VW Hydrae formed by all PC data. A small amplitude period oscillation is seen. After the periodic change was removed, the residuals are displayed in the lower panel.

solution leads to the following equation,

$$\begin{aligned}(O-C)_3 \;=\; & -0.0005(\pm 0.0001) \\ & +0.0048(\pm 0.0004)\sin[0.1518^\circ \times E + 147.0^\circ(\pm 3.3^\circ)]. \end{aligned} \tag{4}$$

This equation reveals another periodic variation with a period of 8.75 yr and a small amplitude of 0.0048 d. The residuals after the small-amplitude oscillation removed are shown in the lower panel of Figure 4 where the scatter of those residuals is usually less than 0.001 d and no changes can be traced there suggesting that Equation (4) describes the general $(O-C)_3$ trend well.

## 4 MECHANISMS FOR THE ORBITAL PERIOD VARIATIONS OF VW HYDRAE

### 4.1 Mass Transfer between both Components

The long-term general trend of the $(O-C)_1$ curve shows an upward parabolic variation that indicates an increasing period at a rate of $dP/dt = +6.34 \times 10^{-7}$ d yr$^{-1}$ (dashed line in the upper panel of Fig. 2). VW Hydrae was classified as an Algol-type eclipsing binary (e.g., Burki et al. 2005) where the secondary is expected to fill the critical Roche lobe, while the primary is detached. The continuous period increase can be explained as a mass transfer from the less massive component to the more massive one. By considering a conservative mass transfer (with no magnetic effect) and by using the absolute parameters derived by Burki et al. (2005), a calculation with the the following equation (e.g., Kwee 1958),

$$\Delta P/P = 3(M_1/M_2 - 1)\Delta M_1/M_1, \tag{5}$$

yields a mass transfer rate of $dM_2/dt = 7.89 \times 10^{-8}\, M_\odot$ yr$^{-1}$.

The time-scale of the mass transfer and period change are computed to be $\tau_M = M_2/\dot{M}_2 = 9.6 \times 10^6$ yr and $\tau_P = P/\dot{P} = 4.3 \times 10^6$ yr. With the values of $T_2$ and $R_2$ determined by Burki et al. (2005), the luminosity of the secondary component is estimated as $L_2 = 5.58\, L_\odot$. Then, the thermal and nuclear time-scales of the secondary component star can be computed by using the following equations,

$$\tau_{\rm Th} = 2 \times 10^7 {M_2}^2/L_2 R_2, \tag{6}$$

and

$$\tau_N = 10^{11} M_2/L_2, \tag{7}$$

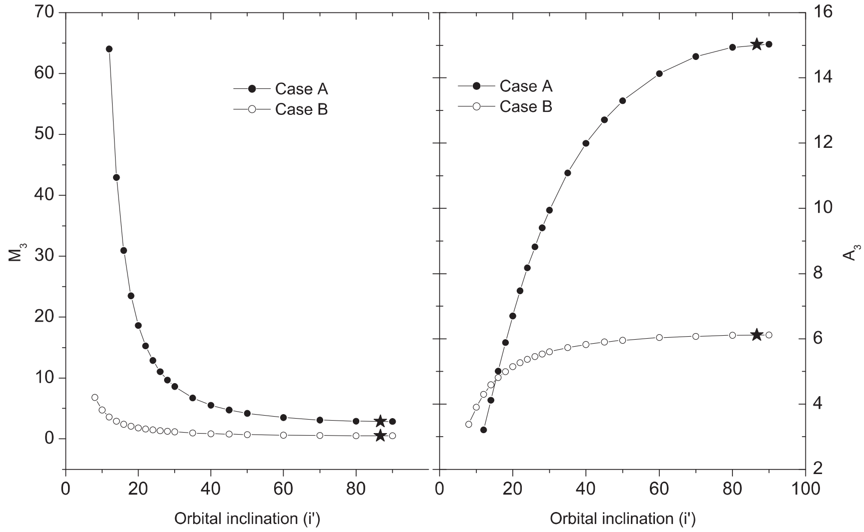


**Fig. 5** Relations between the masses or orbital radii and the orbital inclinations of the additional components. The stars refer to the positions where the components are coplanar to the orbit of the eclipsing pair (VW Hydrae).

where $M_2$, $R_2$, and $L_2$ are the mass, the radius, and the luminosity of the less massive component. The results are $\tau_{\mathrm{Th}} \sim 6.13 \times 10^5$ yr and $\tau_N \sim 1.36 \times 10^{10}$ yr. Therefore, we have $\tau_{\mathrm{Th}} < \tau_M < \tau_N$. This indicates that both the thermal and nuclear mass transfers cannot be used to interpret the observed period change. Recently, a new mechanism based on the period decrease that can be caused by angular momentum (AM) transfer from central binary stars to a circumbinary disk was proposed by Chen et al. (2006). The binary VW Hydrae may undergo a mass transfer in a thermal time-scale, and the period increase observed may be caused by a combination of the mass transfer from the secondary to the primary and the AM transfer from the binary system to the circumbinary disk. Details of the mechanism are needed in further investigations.

### 4.2 The Presence of Additional Components

After the long-term rapid period increase was subtracted from the $(O-C)_1$ curve, two periodic variations were found (as shown in the $(O-C)_2$ and $(O-C)_3$ diagrams). Since the secondary component of VW Hydrae is a cool star (Sp.=F9III), the period oscillations are expected to be caused by the magnetic activity circles, i.e., the Applegate mechanism (e.g., Applegate 1992; Lanza 1998). However, a recent investigation by Lanza (2006) suggests that the Applegate mechanism is not adequate for interpreting the orbital period modulation of close binary stars with a late-type secondary, which includes Algols. Moreover, some recent studies have shown that cyclic period changes are also popular for early-type binaries (e.g., Qian et al. 2006; Qian et al. 2007), which were plausibly interpreted by a light-travel time effect (LTTE) via the presence of additional bodies. Therefore, we think that the plausible mechanism which caused the cyclic period changes of VW Hydrae is the LTTE.

Since the observations do not cover a whole O-C cycle (see Figs. 3 and 4), information on the orbital eccentricity of the additional bodies is not clear. By considering that those additional components are moving in circular orbits, parameters of the additional components were calculated for both cases of LTTEs (Case A and B). The mass functions were computed with the following equations,

$$f(m) = \frac{4\pi^2}{GT^2} \times (a'_{12} \sin i')^3, \tag{8}$$

**Table 3** Parameters for Two Cases of Light-time Effects in VW Hydrae

| Parameters | Case A | Case B | Units |
|---|---|---|---|
| $T$ | 51.5(assumed) | 8.75(assumed) | yr |
| $A_{\rm am}$ | $0.0639(\pm 0.0048)$ | $0.0048(\pm 0.0004)$ | d |
| $a'_{12}\sin i'$ | $11.07(\pm 0.83)$ | $0.83(\pm 0.07)$ | A.U. |
| $f(m)$ | $0.51(\pm 0.11)$ | $7.5(\pm 1.3)\times 10^{-3}$ | $M_\odot$ |
| $M_3(i'=90^\circ)$ | $2.84(\pm 0.50)$ | $0.53(\pm 0.08)$ | $M_\odot$ |
| $M_3(i'=70^\circ)$ | $3.10(\pm 0.52)$ | $0.56(\pm 0.08)$ | $M_\odot$ |
| $M_3(i'=50^\circ)$ | $4.20(\pm 0.65)$ | $0.70(\pm 0.09)$ | $M_\odot$ |
| $M_3(i'=30^\circ)$ | $8.60(\pm 1.36)$ | $1.15(\pm 0.13)$ | $M_\odot$ |
| $a_3(i'=90^\circ)$ | $15.03(\pm 3.41)$ | $6.12(\pm 1.26)$ | A.U. |
| $a_3(i'=70^\circ)$ | $14.65(\pm 3.15)$ | $6.08(\pm 1.18)$ | A.U. |
| $a_3(i'=50^\circ)$ | $13.30(\pm 2.53)$ | $5.96(\pm 0.99)$ | A.U. |
| $a_3(i'=30^\circ)$ | $9.94(\pm 1.81)$ | $5.60(\pm 0.81)$ | A.U. |

and

$$a'_{12}\sin i' = A_{\rm am}\times c, \tag{9}$$

where $A_{\rm am}$ is the amplitude of the O-C oscillation and $c$ is the speed of light. The values of the masses and the orbital radii of the additional components for several different values of $i'$ were estimated by using the following equation,

$$f(m) = \frac{(M_3\sin i')^3}{(M_1+M_2+M_3)^2}. \tag{10}$$

The corresponding results are shown in Table 3. The relations between the orbital inclination $i'$ and $M_3$ or $A_3$ for both cases of LTTE are plotted in Figure 5.

## 5 DISCUSSION AND CONCLUSIONS

As in the cases of RX Hydrae (Qian 2000), SX Draconis (Qian 2002), SW Lyncis (Qian et al. 2002; Erdem et al. 2007a), TZ Lyrae (Yang et al. 2007), RR Draconis (Qian et al. 2002), TW Draconis (Qian & Boonrucksar 2002), TT Andromedae (Erdem et al. 2007b), and S Equulei (Qian & Zhu 2002), rapid period increase was found in VW Hydrae. The evolutionary theory of Algol-type binary stars has suggested that they should be in a slow mass transfer stage on a nuclear time-scale (e.g., Paczyński 1971). However, it is shown that the time-scale of the mass transfer is usually much shorter than the nuclear time-scales of the secondary component stars. Taking into account the AM transfer from the central binary to the circumbinary disk, mass transfer may happen according to a thermal time-scale.

Since the Applegate mechanism is inadequate for causing the orbital period modulation of Algols (Lanza 2006), the two cyclic changes can be plausibly interpreted by the LTTE via the presence of two additional bodies. The analysis in the previous section indicates that the mass of the tertiary component is no less than $0.53\,M_\odot$, while that of the fourth body is $M_4 > 2.84\,M_\odot$. Based on their observations in the $U$-band, Kviz & Rufener (1987) argued that there exists an ultraviolet source in the system that must be eclipsed during the secondary eclipse. We suspected that the ultraviolet source may be one of the additional bodies. If the fourth component is a main-sequence star, it should be very luminous and can be detected easily. On the other hand, since no signal of the additional components was reported by Burki et al. (2005) from their photometric and spectroscopic observations, it is possible that the fourth component is an unseen neutron star or black hole. However, the data do not cover a whole cycle for both periodic variations (as seen in Figs. 3 and 4). In order to check the period changes of VW Hydrae proposed here, more precise eclipse times are required in the future.

**Acknowledgements** This work is partly supported by the Yunnan Natural Science Foundation (No. 2005A0059M), the National Natural Science Foundation of China.(Nos. 10573032, 10433030 and 10573013), Chinese Academy of Sciences (No.O8ZKY11001) and the Ministry of Science and Technology of the Peoples Republic of China through grant 2007CB815406. New observations of

VW Hya that we used were obtained from the 1.0 m telescope at Yunnan Observatory. The authors thank Zhu L. Y. and He J. J. for allocation of observing time at Kunming. Special thanks are given to the anonymous referee for his or her useful comments.

## References

Applegate, J. H. 1992, ApJ, 385, 621
Burki, G., Barblan, F., & Carrier, F. 2005, New Astronomy, 11, 197
Caton, D. B., & Smith, A. B. 2005, IBVS, 5595
Chen, W. C., Li, X.-D., & Qian, S. B. 2006, ApJ, 649, 973
Diethelm, R. 2004, IBVS, 5543
Erdem, A., Doğru, S. S., Bakis, V., et al. 2007a, AN, 328, 543
Erdem, A., Soydugan, F., Doğru, S. S., et al. 2007b, New Astronomy, 12, 613
Hoffmeister, C. 1929, AN, 236, 233
Kreiner, M. J., Kim, C.-H., & Nha, I.-S. 2001, aocd.book, 1304
Kviz, Z., & Rufener, F. 1987, IBVS, 2987
Kwee, K. 1958, Bull. Astron. Inst. Netherlands, 14, 131
Lanza, A. F. 2006, MNRAS, 369, 1773
Lanza, A. F., Rodonò, M., & Rosner, R. 1998, MNRAS, 296, 893
Locher, K. 1974, BBSAG Bull., 13
Locher, K. 1975, BBSAG Bull., 21
Locher, K. 1978, BBSAG Bull., 16
Locher, K. 1978, BBSAG Bull., 40
Locher, K. 1981, BBSAG Bull., 53
Locher, K. 1982, BBSAG Bull., 59
Locher, K. 1983, BBSAG Bull., 64
Locher, K. 1987, BBSAG Bull., 82
Locher, K. 1988a, BBSAG Bull., 86
Locher, K. 1988b, BBSAG Bull., 87
Locher, K. 1989, BBSAG Bull., 91
Locher, K. 1990, BBSAG Bull., 93
Locher, K. 1992, BBSAG Bull., 102
Locher, K. 2001, BBSAG Bull., 124
Nagai, K. 2003, Var.Star Bull., 40, 1
Pagaczewski, J. 1934, Acta Astr.ser.b, 2, 19
Pagaczewski, J. 1931, Acta Astr.ser.b, 2, 28
Pagaczewski, J. 1945, Circ.Warsaw Obs., 21, 5
Paczyński, B. 1971, ARA&A, 9, 183
Qian, S.-B. 2000, A&AS, 146, 377
Qian, S.-B. 2002, Ap&SS, 282, 399
Qian, S.-B., & Boonrucksar, S. 2002, New Astronomy, 7, 435
Qian, S.-B., Liu, L., & Kreiner, J. M. 2006, New Astronomy, 12, 117
Qian, S.-B., Yuan, J.-Z., Liu, L., et al. 2007, MNRAS, 380, 1599
Qian, S.-B., & Zhu, L.-Y. 2002, ApJS, 142, 139
Qian, S.-B., Zhu, L.-Y., & Boonrucksar, S. 2002, A&A, 396, 609
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Wilson, R. E. 1994, PASP, 106, 921
Yang, Y. G., & Yin, X. G. 2007, ChJAA (Chin. J. Astron. Astrophys.), 7, 258