RAA 2019 Vol. **19** No. **7**, 94(6pp) doi: 10.1088/1674–4527/19/7/94

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Research in Astronomy and Astrophysics

Photometric investigation of the eclipsing binary TX Herculis observed by LUT

Li-Ying Zhu[1,2,3,4], Xiao-Man Tian[1,2,3,4], Xiao Zhou[1,2,3], Lin-Jia Li[1,2,3] and Zhi-Hua Wang[1,2,3,4]

[1] Yunnan Observatories, Chinese Academy of Sciences, Kunming 650216, China; *zhuly@ynao.ac.cn*

[2] Center for Astronomical Mega-Science, Chinese Academy of Sciences, Beijing 100101, China

[3] Key Laboratory for the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650216, China

[4] University of the Chinese Academy of Sciences, Beijing 100049, China

Received 2018 September 12; accepted 2019 January 11

Abstract The lander of China's *Chang'E-3* spacecraft is equipped with a 15-cm telescope that is very useful for monitoring celestial objects in the ultraviolet (UV) band (245–340 nm). The Lunar-based Ultraviolet Telescope (LUT) is the first long-term lunar-based astronomical observatory, that can make uninterrupted observations of a target from the Moon. Here we present the continuous complete UV light curve of the eclipsing binary TX Herculis (TX Her). The analysis of the light curve suggests that TX Her is a detached binary. The dip in the light curve was explained by the emergence of a stellar dark spot on the less massive F0 type component. The cyclic change of arrival eclipse times for the system reveals that it contains an additional stellar companion with a minimal mass of 0.35 $M_\odot$ and a period of 48.92 yr, which is supported by the detected light contribution of the third body from light curve analysis. This third body may play an important role in the formation of the present short-period system TX Her.

Key words: stars: binaries : close — stars: binaries : eclipsing — stars: individuals (TX Herculis) — stars: multiple system — stars: activity

1 INTRODUCTION

The Lunar-based Ultraviolet Telescope (LUT), which is mounted on the *Chang'E-3* lander, has a field view of $1.27^\circ \times 1.27^\circ$ that is capable of detecting objects at a brightness as low as magnitude 13.5 in the ultraviolet (UV) band (245–340 nm) (Cao et al. 2011; Wen et al. 2014). It can point to various targets automatically. The thin atmosphere and slow rotation of the Moon allow extremely long and uninterrupted observations of a target. This allows continuous observations of close binaries and enables studying their uninterrupted light variation behaviors (Meng et al. 2015; Wang et al. 2015). Several binary stars have been investigated by using LUT data (e.g., Qian et al. 2015a; Zhu et al. 2016; Zhou et al. 2016; Liao et al. 2016a,b).

TX Herculis (TX Her=HD 156965=BD+422823= GSC 03081–01297=HIP 84670) is an eclipsing binary system that consists of an A5-type star as the primary and an F0-type star as the secondary (Petrie 1950; Popper 1970). Popper (1970) also analyzed its radial velocity curve and derived the mass ratio of this system based on spectrographic observations. Its eclipsing nature was discovered by Zinner (1912). The primary component of TX Her is a peculiar star, in which the Ca II K line is considerably weaker compared to stars of the same spectral type (e.g., Smalley et al. 2014). TX Her is one of the 73 eclipsing Am binaries discovered up till now (Tian et al. 2018). Most such stars are members of close binaries (e.g., Abt & Levy 1985). The eclipses of those binaries could provide a good opportunity to measure physical parameters and help in understanding properties of Am binaries. Many authors studied this system photometrically, e.g., Botsoula (1956), Plavec et al. (1960), Botsula (1968), Vetesnik & Papousek (1973), van Hamme (1982), Lacy et al. (1987), Kreiner & Zola (1989), Wolf (1990), Ak et al. (2004) and Erdem et al. (2011). Most of them found a cyclic change in its orbital period and explained this variation by the light-time effect due to a third body. The latest research about TX Her was carried out by Erdem et al. (2011). They analyzed their $BVRI$ light curves, derived the absolute parameters of this

Table 1 UV Band Observations of TX Her (the First Five Observations)

JD (Hel.)	$\Delta(m)$
2456943.0431	9.991
2456943.0442	9.982
2456943.0453	9.989
2456943.0464	9.992
2456943.0475	10.02

Table 2 Photometric Solutions of TX Her

Parameter	Value (without spot)	Value (with spot)
T_1 (K)	8180 (fixed)	8180 (fixed)
$g_1 = g_2$	1.00 (fixed)	1.00 (fixed)
$A_1 = A_2$	1.00 (fixed)	1.00 (fixed)
q (M_2/M_1)	0.895 (fixed)	0.895 (fixed)
T_2/T_1	0.9122 ± 21	0.9213 ± 24
i (°)	87.2 ± 0.2	88.3 ± 0.2
Ω_1	7.352 ± 0.081	7.484 ± 0.090
Ω_2	6.929 ± 0.056	6.700 ± 0.052
$L_1/L_{\rm total}$	0.5767 ± 0.0043	0.5300 ± 0.0055
$L_3/L_{\rm total}$	0.0757 ± 0.0019	0.0943 ± 0.0018
r_1 (pole)	0.1547 ± 0.0019	0.1518 ± 0.0020
r_1 (point)	0.1562 ± 0.0020	0.1531 ± 0.0021
r_1 (side)	0.1553 ± 0.0019	0.1523 ± 0.0020
r_1 (back)	0.1560 ± 0.0020	0.1530 ± 0.0021
r_2 (pole)	0.1519 ± 0.0014	0.1580 ± 0.0014
r_2 (point)	0.1535 ± 0.0015	0.1598 ± 0.0015
r_2 (side)	0.1524 ± 0.0014	0.1586 ± 0.0014
r_2 (back)	0.1533 ± 0.0015	0.1596 ± 0.0014
latitude (deg)		101.2 ± 8.1
longitude (deg)		41.4 ± 1.8
radius (radian)		0.48 ± 0.04
$T_f(T_s/T_0)$		0.87 ± 0.05
$\sum(O-C)^2$	0.045	0.042

system and updated the parameters of the third body that may surround the central binary.

The orbital period of the binary is about $2.0598^{\rm d}$ indicating that it will take weeks to obtain a complete light curve at one Earth-based observatory, and this complete light curve could not be continuous (Erdem et al. 2011). TX Her was observed by LUT from 2014 October 12 to 14. The first continuous complete light curve in the UV band was obtained and is shown in Figure 1 with open circles, where the asymmetric light curve with unequal heights of the two maxima can be seen.

2 LUT LIGHT CURVE AND PHOTOMETRIC SOLUTIONS

TX Her was monitored by employing LUT with a UV enhanced back illuminated CCD in October 2014. The data processing was performed by Meng et al. (2015). The first continuous complete light curve was obtained and is graphed in Figure 1. Its corresponding photometric accuracy is about 0.015 mag. All the observations are tabulated in Table 1. The full table is online at `http://paperdata.china-vo.org/ms2018-0248/ms2018-0248Table1.dat`. The light curve observed by LUT was analyzed by using the Wilson-Devinney (W-D) method (Wilson & Devinney 1971; Wilson 1990, 1994). During the solution process, the effective temperature of star 1 (the primary component star that is eclipsed at phase 0.0) was chosen as $T_1 = 8180\,{\rm K}$ according to the spectral type of A5V (Petrie 1950; Popper 1970; Cox 2000). The gravity-darkening coefficients $g_1 = g_2 = 1.0$ and the bolometric albedo $A_1 = A_2 = 1.0$ were used because the two components are early-type stars (A5+F0). Limb-darkening coefficients were taken from the table of van Hamme (1993). The mass ratio q of this binary system was fixed at 0.895, which was obtained by Popper (1970) based on his radial velocity analysis. The adjustable parameters were: the orbital inclination i; the mean temperature of star 2, T_2; the monochromatic luminosity of star 1, L_1; the dimensionless potentials of stars 1 and 2, Ω_1 and Ω_2 respectively; and the third light l_3.

As shown in Figure 1, there is an obvious brightness dip around HJD 2456944.8. It was pointed out that the light curve of TX Her appears to be very disturbed at maximum (e.g., Gyldenkerne et al. 1970). Some perturbations in the shapes of the minima were reported by Bakos & Tremko (1974) who attributed those perturbations to be the results of chromospheric activity in the secondary star. We employed the spot model to fit the light curve, and found that the brightness dip could be explained by the emergence of a dark spot on the F0-type component. The final converged photometric solutions with and without a spot are summarized in Table 2. The spot has four parameters, they are: the latitude of spot center (θ) in degrees, the longitude of spot center (ϕ) in degrees, spot angular radius (r) in radians and the spot temperature factor ($T_f = T_d/T_0$, T_f is the ratio between the spot temperature T_d and the photosphere surface temperature T_0 of the star). The corresponding theoretical light curves are plotted in Figure 1 with the solid line (with spot) and dashed line (without spot). Figure 2 shows the geometric structure of TX Her at phases 0.0, 0.25, 0.5 and 0.75. By using the determined photometric solutions together with those spectroscopic elements given by Popper (1970), the masses, radii and luminosities of the two component are derived as: $M_1 = 1.61\,M_\odot$, $M_2 = 1.44\,M_\odot$, $R_1 = 1.53\,R_\odot$,

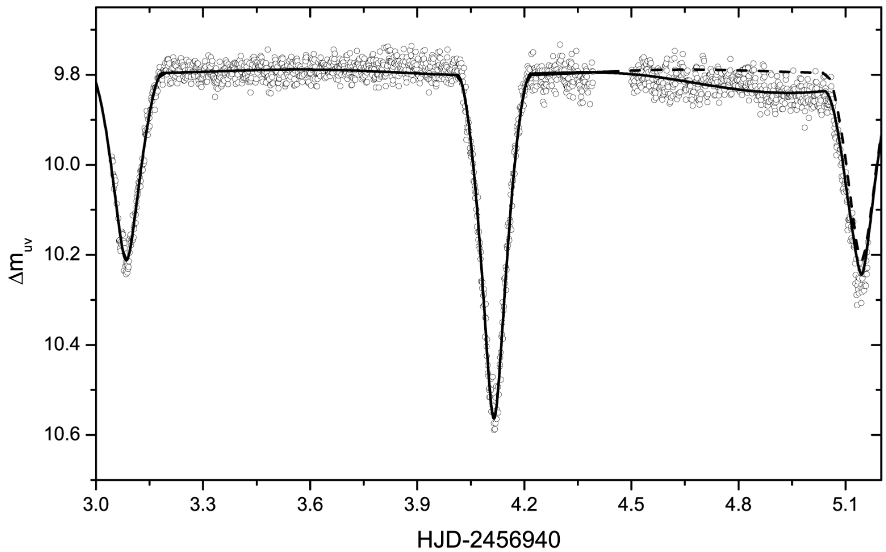

Fig. 1 Light curve of TX Her obtained by LUT from the Moon. *Open circles* refer to observations in the UV band, while the *solid line* to the theoretical light curve with a dark spot on the secondary star and the *dashed line* to the theoretical light curve without the spot.

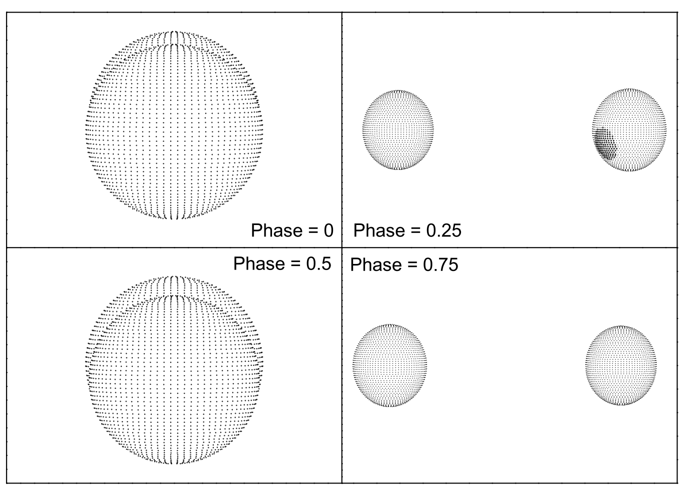

Fig. 2 Geometrical structure of TX Her at phases 0.0, 0.25, 0.5 and 0.75. Both component stars are well inside their critical Roche Lobes.

$R_2 = 1.51\,R_\odot$, $L_1 = 9.44\,L_\odot$, $L_2 = 6.56\,L_\odot$, respectively.

3 VARIATIONS IN THE $O - C$ DIAGRAM

Three eclipse times of TX Her were determined based on LUT data. They are listed in Table 3 where "P" refers to the primary minimum, while "S" to the secondary one. Since TX Her has comparatively deep and sharp eclipse minima and it is relatively bright ($V = 8.12$ mag.), the binary system has been an attractive target for astronomical observers for almost a century. It was intensively observed visually and photographically before HJD 2433054. Then this binary was monitored photoelectrically and with charge-coupled device (CCD)-based analysis, and many eclipse

Table 3 Eclipse Times for TX Her

Name	Min.	HJD	Error
TX Her	S	2456943.08527	0.00044
TX Her	P	2456944.11476	0.00036
TX Her	S	2456945.14261	0.00081

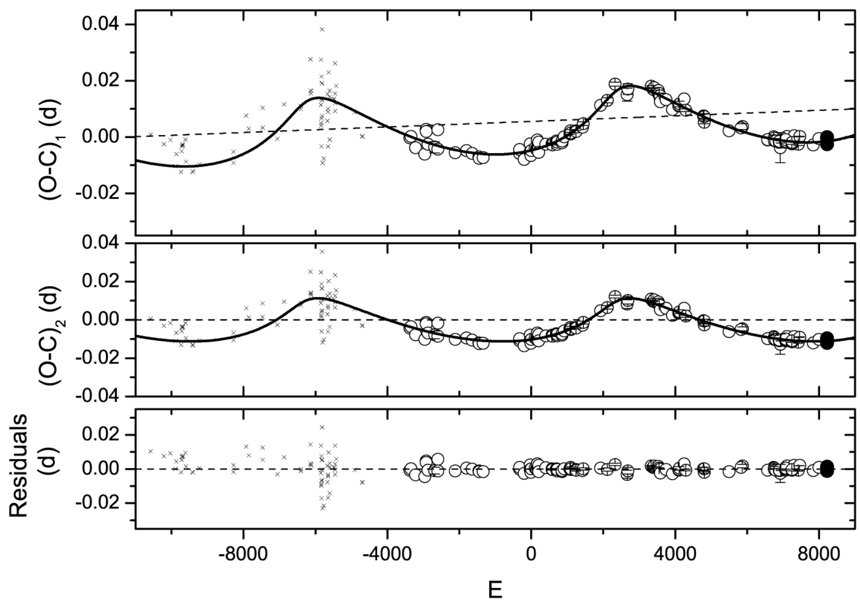

Fig. 3 $O-C$ diagrams of TX Her. *Crosses* refer to visual or photographic observations, while *open circles* to CCD or photoelectric data. LUT observations are plotted as *solid dots*. The $(O-C)_1$ curve in the upper panel represents a combination of a new linear ephemeris (the *dashed line*) and a cyclic variation (*solid line*). The $(O-C)_2$ diagram with respect to the linear ephemeris is shown in the middle panel where the cyclic change is seen more clearly. Residuals after removing all of the changes are displayed in the lower panel.

Table 4 Orbital Parameters of the Third Body in TX Her

Parameter	Value
Revised epoch, ΔT_0 (d)	$+0.0055(\pm 0.0004)$
Revised period, ΔP_0 (d)	$+4.93(\pm 0.53)\times 10^{-7}$
Longitude of the periastron passage, ω (deg)	$52.6(\pm 4.2)$
Periastron passage, T (HJD)	$2444841.3(\pm 193.5)$
Light-time effect amplitude, K (d)	$0.0119(\pm 0.0004)$
Eccentricity, e	$0.54(\pm 0.05)$
Orbital period, P_3 (yr)	$48.92(\pm 0.82)$
d_3 ($i'=90°$) (AU)	$18.0(\pm 0.9)$
Mass function, $f(m)$ ($M_\odot$)	$3.66(\pm 0.37)\times 10^{-3}$
Projected masses, $M_3 \sin i'(M_\odot)$	$0.35(\pm 0.01)$

times were published (e.g., Kreiner & Zola 1989; Ak et al. 2004; Erdem et al. 2011; Hubscher 2016; Tzouganatos et al. 2016). The $(O-C)_1$ values with respect to the linear ephemeris from the $O-C$ gateway (`http://var.astro.cz/ocgate/`),

$$\mathrm{Min.I} = \mathrm{HJD}\,2440008.362 + 2.05980944 \times E, \qquad (1)$$

were computed. The corresponding $(O-C)_1$ diagram is shown in the upper panel of Figure 3 along with the epoch number E. The crosses in the panel refer to photographic and visual (hereafter "PV") data and open circles to photoelectric and CCD (hereafter "PC") observations. The solid dots represent LUT data. As displayed in the upper panel of Figure 3, the $(O-C)_1$ values of the photographic and visual times of light minimum exhibited a large scatter (up to 0.03^{d}). Therefore, we chose different weights for these data during the fitting. A weight of 1 was assigned to the "PV" observations, while a weight of 100 was assigned to the "PC" data.

As seen in Figure 3, the $(O-C)_1$ curve manifests a cyclic change that could be explained by the presence of a third body in the binary system (e.g., Liao & Qian 2010; Zhao et al. 2018; Zhang et al. 2018). By considering a general case with an eccentric orbit (e.g., Irwin 1952; Qian 2002, 2003; Li et al. 2018), the following equation (solid line in the upper panel of Fig. 3),

$$(O-C)_1 = \Delta T_0 + \Delta P_0 \times E + \tau, \qquad (2)$$

was applied to describe the $(O-C)_1$ diagram. ΔT_0 and ΔP_0 in the equation are the revised epoch and period respectively. The cyclic term, τ, is given by the equation,

$$\begin{aligned}\tau &= K[(1-e^2)\frac{\sin(\nu+\omega)}{1+e\cos\nu} + e\sin\omega] \\ &= K[\sqrt{1-e^2}\sin E^*\cos\omega + \cos E^*\sin\omega], \qquad (3)\end{aligned}$$

which is caused by the light-time effect of the third body. ν in Equation (3) is the true anomaly, E^* is the eccentric anomaly and K is described as $K=\frac{a_{12}\sin i'}{c}$ ($a_{12}\sin i'$ is the projected semi-major axis). To solve Equation (3), the two correlations,

$$N = E^* - e \sin E^*, \quad (4)$$

and

$$N = \frac{2\pi}{P_3}(t - T) \quad (5)$$

are used. N in Equations (4) and (5) is the mean anomaly and t is the time of light minimum.

During the solution, a weighted Levenberg–Marquardt method was implemented. The result indicates that the $(O - C)_1$ curve shows a cyclic change with a period of $48.92\,\mathrm{yr}$ and an amplitude of $0.0119\,\mathrm{d}$ that is more clearly seen in the middle panel. The residuals based on Equation (2) are displayed in the lower panel of Figure 3. The parameters of the third body are listed in Table 4. The stellar companion orbits the central binary in an eccentric orbit ($e \sim 0.54$). By assuming that the orbital inclination is $i' = 90°$, its orbital separation is computed as $\sim 18\,\mathrm{AU}$ (1 AU is the separation between the Earth and the Sun).

4 DISCUSSION AND CONCLUSIONS

TX Her is an eclipsing binary with an orbital period of 2.0598^{d}, indicating that it is very difficult to obtain a complete light curve at a single Earth-based observatory. We present the first continuous and uninterrupted UV band complete light curve observed by LUT. By using the W-D code, we analyze this light curve. Our photometric solutions indicate that it is a detached binary with an orbital inclination of $i = 88.3°$, which is consistent with previous studies (Vetesnik & Papousek 1973; Lacy et al. 1987; Erdem et al. 2011). Our continuous light curve shows a brightness dip around HJD 2456944.8, which is different from previous symmetric light curves. This dip is explained by the presence of a stellar dark spot on the F0-type component. Such asymmetry in EA light curves is usually found in late type binary systems (Zhang et al. 2014a,b; Qian et al. 2019), but has been seldom found in early type systems like TX Her. The solution indicates that the temperature of the dark spot is about 980 K lower than that of the stellar photosphere on the less massive component star. It is similar to that of a typical sunspot. However, the dark spot covers about 3.8% of the total photospheric surface, which is much larger than that of a spot on the Sun (the area of a sunspot is usually less than 1% of the photospheric surface of the Sun). It is possible that the spot may be composed of a group of small spots.

The eclipse times were used to investigate variations in the orbital period by analyzing the $O - C$ diagram. Third bodies have been detected in types of close binaries based on investigation of the $O - C$ curves (e.g., Qian & Yang 2005; Qian et al. 2007, 2015b; Zhu et al. 2009, 2011; Yang et al. 2012, 2014). Such a third body causes the binary to periodically move closer to or farther away from the Sun and the eclipse time is cyclically advanced or delayed. The cyclic change in the $O - C$ diagram reveals that there is a third body in TX Her (e.g., Kreiner & Zola 1989; Ak et al. 2004; Erdem et al. 2011). Erdem et al. (2011) published the latest result from the $O - C$ analysis and suggested that this third body has a minimal mass of $0.39\,M_\odot$ and period of 51.6 yr. We extended the $O - C$ curve for more than four years by adding our timings and those from literature. Then we reanalyzed the $O - C$ curve and updated the parameters of the third body with a minimal mass of $0.35\,M_\odot$ and period of $48.92\,\mathrm{yr}$; more parameters can be found in Table 4. Our photometric solutions in Table 2 indicate that it contributes about 9.4% to the total brightness of the system in the UV band.

Based on *Kepler* data, some close-in tertiary companions were found to be orbiting eclipsing binary stars by the method of mutual eclipses (e.g., Carter et al. 2011; Derekas et al. 2011). It was estimated by Orosz (2015) that 15% to 20% of *Kepler* eclipsing binaries have close-in tertiary companions. They are an important source to test theories of close star formation and evolution. The orbital separation of the two components of TX Her is only about $9.8\,R_\odot$ indicating that the two component stars cannot form independently during the pre-main-sequence phase because they would have been inside each other. How did they form? The third component should have played an important role. They may have been originally wider binaries that were brought closer together due to interaction with the third body during early interaction and/or late dynamical evolution (e.g., Pribulla & Rucinski 2006; D'Angelo et al. 2006; Qian et al. 2006).

Acknowledgements The authors thank the LUT group including Drs. J.-Y. Wei, X.-M. Meng, X.-H. Han and J. Wang for helping in observations and data reduction. This work is partly supported by the National Natural Science Foundation of China (Grant Nos. 11573063 and 11611530685), the Key Science Foundation of Yunnan Province (Grant No. 2017FA001), CAS "Light of West China" Program and CAS Interdisciplinary Innovation Team.

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