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Research Article

The Photometric Investigation of V921 Her Using the Lunar-Based Ultraviolet Telescope of Chang'e-3 Mission

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The light curve of V921 Her in ultraviolet band observed by the Lunar-based Ultraviolet Telescope (LUT) is analyzed by the Wilson-Devinney code. Our solutions conclude that V921 Her is an early type marginal contact binary system with an additional close-in component. The binary system is under poor thermal contact with a temperature difference of nearly 700 K between the two components. The close-in component contributes about 19% of the total luminosity in the triple system. Combining the radial velocity study together with our photometric solutions, the mass of the primary star and secondary one is calculated to be $M_1 = 1.784\ (\pm 0.055) M_\odot$, $M_2 = 0.403\ (\pm 0.012) M_\odot$. The evolutionary scenario of V921 Her is discussed. All times of light minimum of V921 Her available in the bibliography are taken into account and the $O-C$ curve is analyzed for the first time. The most probable fitting results are discussed in the paper, which also confirm the existence of a third component ($P_3 = 10.2$ year) around the binary system. The period of V921 Her is also undergoing a continuously rapid increase at a rate of $dP/dt = +2.79 \times 10^{-7}$ day · year^{-1}, which may be due to mass transfer from the less massive component to the more massive one.

1. Introduction

In December 2013, the Chinese Lunar Exploration Program carried out the Chang'e-3 mission [1], which sent a LUT to the surface of the moon. LUT is the first robotic astronomical telescope deployed on the moon surface. It has been working for nearly two years since landing on the moon. Eclipsing binaries are among its observational targets. We have obtained some light curves (LCs) to be analyzed, and V921 Her is a such one.

The light variability of V921 Her (HIP 82344, $V = 9.49^m$) was first discovered by the Hipparcos mission [2] and the Hipparcos Catalogue gave its spectral type to be A5. Later, Rucinski et al. [3] carried out the radial velocity study of V921 Her. The results determined that V921 Her was an A-subtype contact binary system with its spectral type to be A7IV. They obtained its mass ratio (M_2/M_1) to be $q = 0.226\ (\pm 0.005)$. Compared with other W UMa type close binary systems of the same spectral type, V921 Her has a quite long period, which is $P = 0.877366$ d. The first photometric analysis of V921 Her was done by Gazeas et al. [4]. They redetermined the mass ratio of the binary system to be $q = 0.244$ and set the effective temperature of the primary star to be $T_1 = 7700$ K. Their results concluded that V921 Her was a shallow contact binary system. However, Karami and Mohebi [5] and Karami et al. [6] also obtained the mass ratio of V921 Her, both of which were consistent with those determined by Rucinski et al. [3].

Orbital period research is a very important part for close binary systems since the period variations contain information about the dynamic interaction occurring between the components of binary systems. However, the period change investigation of V921 Her has been neglected since it was discovered. In the present work, light curve of V921 Her

Table 1: New CCD times of light minimum for V921 Her.

JD (hel.)	Error (days)	Min.
2457056.3349	±0.0015	I
2457056.7733	±0.0019	II

observed by the LUT is analyzed with the Wilson-Devinney (W-D) code, and its period variations are investigated for the first time. The results will give us comprehensive understanding to the physical properties and dynamical evolution of this contact binary system.

2. New Photometric Observations

The LUT is a 150 mm, F/3.75 Ritchey-Chretien telescope working at a Nasmyth focus. It is equipped with a UV-enhanced back-illuminated AIMO 1 k CCD with a field of view to be $1.3^\circ \times 1.3^\circ$; thus the CCD pixel scale is $4.7''$ pixel^{-1}. The passband of filter is about 245–345 nm, with its peak at 250 nm [7].

The light curve of V921 Her was observed continuously in ultraviolet band by the LUT on February 2, 2015. PHOT subroutine (measured magnitudes for a list of stars) of the IRAF (The Image Reduction and Analysis Facility is hosted by the National Optical Astronomy Observatories in Tucson, Arizona, at URL http://iraf.noao.edu/.) aperture photometry package was used to reduce the observed images [8].

Basing on the observational data, two times of light minimum are determined using the least-squares method [9], which are listed in Table 1.

The phase of our observations is calculated with the following linear ephemeris:

$$\text{Min.I (HJD)} = 2457056.3349\,(15) + 0^{d}.877379 \times E. \quad (1)$$

3. Investigation of the Orbital Period

The orbital period variations of a binary star reveal dynamic interactions between its components or the gravitational interactions between the binary system and the close-in component orbiting around it. During this work, all times of light minimum of V921 Her available in the bibliography are taken into account and listed in Table 2. All of the minimum data are observed with CCD camera. The $(O - C)$ (observed times of light minimum – calculated times of light minimum) values of all light minima are calculated with the linear ephemeris below:

$$\text{Min.I (HJD)} = 2448500.1250 + 0^{d}.877379 \times E. \quad (2)$$

The Epoch and corresponding $O - C$ values are listed in the third and fourth columns of Table 2, respectively. The origin in time used in (2) is the first minimum light available in the bibliography for V921 Her.

As shown in Figure 1(a), the linear ephemeris in (2) cannot explain the $O - C$ variations efficiently. We consider

Table 2: $(O - C)$ values of light minimum for V921 Her.

JD (hel.) (2400000+)	Min.	Epoch (cycles)	$(O - C)$ (days)	Error (days)	Reference
48500.1250	I	0	0		(1)
51318.2680	I	3212	0.0017		(2)
52790.5033	I	4890	−0.0050	0.0001	(3)
52808.4900	II	4910.5	−0.0046	0.0008	(4)
52840.5150	I	4947	−0.0039	0.0005	(5)
52862.4454	I	4972	−0.0080	0.0013	(5)
53087.9381	I	5229	−0.0017	0.0002	(6)
53095.3998	II	5237.5	0.0023	0.0025	(7)
53131.8020	I	5279	−0.0067	0.0004	(8)
53146.7240	I	5296	−0.0002	0.0003	(8)
53463.4610	I	5657	0.0030	0.0001	(3)
53821.8693	II	6065.5	0.0020	0.0003	(9)
55270.8510	I	7717	−0.0077	0.0002	(10)
55298.9376	I	7749	0.0027	0.0003	(11)
55374.3931	I	7835	0.0036	0.0005	(12)
57056.3349	I	9752	0.0099	0.0015	(13)
57056.7733	II	9752.5	0.0096	0.0019	(13)

Reference: (1) Hipparcos mission [2]; (2) ROTSE project [10]; (3) Pribulla et al. [11]; (4) Brát et al. [12]; (5) Pejcha [13]; (6) Nelson [14]; (7) Krajci [15]; (8) Dvorak [16]; (9) Nelson [17]; (10) Dvorak [18]; (11) Nelson [19]; (12) Brát et al. [20]; (13) present work.

long term increase (or decrease) and periodic variations superposed on the linear ephemeris; then

$$O - C = \Delta T_0 + \Delta P_0 \times E + \frac{1}{2}\frac{dP}{dE} \times E^2 + \tau, \quad (3)$$

where ΔT_0 and ΔP_0 are corrections to the initial ephemeris and period and τ is the periodic element given by Irwin [21] in the case of $e = 0$. Based on the least-squares method, the most probable results of $(O - C)$ curve fitting are given out.

The resulting ephemeris is

$$\begin{aligned} \text{Min.I} = {} & 2448500.1299\,(\pm 0.0004) \\ & + 0^{d}.8773763\,(\pm 0.0000001) \times E \\ & + 3.35\,(\pm 0.09) \times 10^{-10} \times E^2 \\ & + 0^{d}.0052\,(\pm 0.0002) \\ & \cdot \sin\left[0^\circ.08475 \times E + 250^\circ\,(\pm 1^\circ)\right]. \end{aligned} \quad (4)$$

With the quadratic term included in this ephemeris, a continuous period increase, at a rate of $dP/dt = +2.79\,(\pm 0.08) \times 10^{-7}$ day $\cdot$ year^{-1}, is determined. The sinusoidal term reveals a cyclic period change with a period of 10.2 years and an amplitude of 0.00516 days. The residuals from (3) are showed in Figure 1(c).

It has to be mentioned that the data point of $E = 7717$ is not used since it is apparently inconsistent with the following

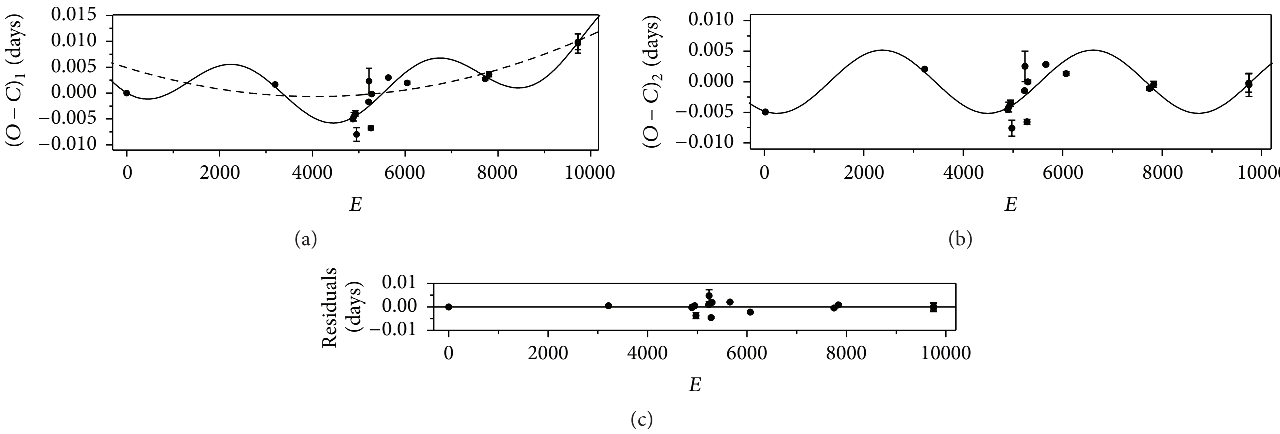

Figure 1: The $(O-C)_1$ values of V921 Her from the linear ephemeris of (2) are presented in (a). The solid line in the panel refers to the combination of an upward parabolic variation and a cyclic change. The dashed line represents the upward parabolic variation which reveals a continuous increase in the orbital period. In (b), the $(O-C)_2$ values with the quadratic part in (3) removed are displayed, where a cyclic change is more clear to be seen. After both the parabolic change and the cyclic variation are removed, the residuals are plotted in (c).

two data points. The large group of minima are between $E = 4800$ and $E = 6000$ cycles; the rest consists of only 6 very small groups of minima widely dispersed over time. To test the evolution of the $O-C$ diagram, more and more data are necessary in the near future.

The orbital period of binary system is a very important parameter. In the present paper, comparing the period published by other researchers and databases, we chose the initial period to be $P = 0^d.877379$, since there is only a very small difference among them. The revised period in (4) is 0.8773763(1), which confirms that the period we used is acceptable.

4. Analysis of the Light Curves

To understand the geometrical structure and physical properties of V921 Her, the observed light curve is analyzed using the W-D code (Version 2013) [22–24]. According to the spectral type (A7IV) and mass ratio ($q = 0.226$) derived by Rucinski et al. [3], the effective temperature of star 1 (star eclipsed at primary minimum light) is set to be $T_1 = 7700$ K [25], and the mass ratio is fixed to $q = 0.226$. Radiative and convective outer envelopes are assumed for star 1 and star 2, respectively. Thus, the bolometric albedo $A_1 = 1$, $A_2 = 0.5$ [26] and the values of the gravity-darkening coefficients $g_1 = 1$, $g_2 = 0.32$ [27] are used. To account for the limb darkening in detail, logarithmic functions are used. The corresponding bolometric and passband-specific limb-darkening coefficients are chosen from Van Hamme's table [28].

During the W-D modeling process, the adjustable parameters are as follows: the orbital inclination i; the mean surface temperature of star 2 (T_2); the monochromatic luminosity of star 1 (L_1); the dimensionless potential of star 1 (Ω_1) and star 2 (Ω_2); and the third light l_3. It is found the solutions converge at both Mode 3 (contact configuration) and Mode 5 (semidetached configuration). The final photometric solutions are listed in Table 3. The theoretical light curves of Mode 3 are displayed in Figure 2 and the theoretical light curves which have not been contaminated by the third light are also plotted with dashed lines. The resulting figure from Mode 5 is very similar to Figure 2. The geometrical structure at phase 0.25 is displayed in Figure 3.

Table 3: Photometric solutions of V921 Her.

Parameter	Solutions	Solutions
Mode	3	5
T_1 (K)	7700 (assumed)	7700 (assumed)
g_1	1.00 (assumed)	1.00 (assumed)
g_2	0.32 (assumed)	0.32 (assumed)
A_1	1.00 (assumed)	1.00 (assumed)
A_2	0.50 (assumed)	0.50 (assumed)
q [M_2/M_1]	0.226 (assumed)	0.226 (assumed)
Ω_1	2.296 (±0.015)	2.303 (±0.022)
Ω_2	2.296 (±0.015)	2.296
Ω_{in}	2.296	2.296
i [°]	75.4 (±3.8)	75.5 (±3.5)
T_2 [K]	7003 (±92)	7011 (±84)
ΔT (K)	697	689
T_2/T_1	0.91 (±0.01)	0.91 (±0.01)
$L_1/(L_1+L_2)$	0.869 (±0.013)	0.867 (±0.010)
$L_3/(L_1+L_2+L_3)$	0.188 (±0.074)	0.189 (±0.059)
r_1 (pole)	0.478 (±0.004)	0.475 (±0.005)
r_1 (side)	0.517 (±0.006)	0.514 (±0.007)
r_1 (back)	0.541 (±0.007)	0.537 (±0.008)
r_2 (pole)	0.241 (±0.005)	0.241
r_2 (side)	0.251 (±0.005)	0.251
r_2 (back)	0.283 (±0.009)	0.283
$\sum \mathrm{res}^2$	$5.3659 * 10^{-6}$	$5.3635 * 10^{-6}$

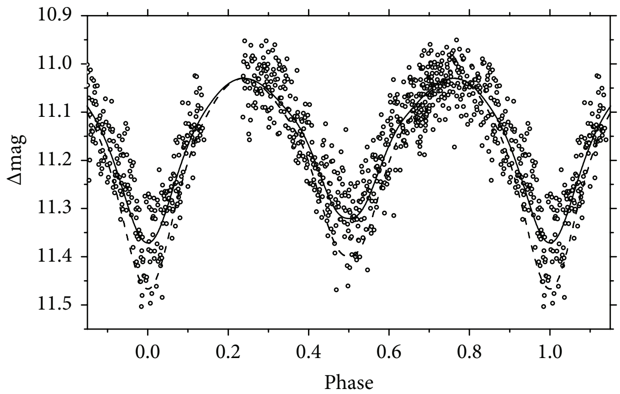

Figure 2: The observed (open circles) and theoretical (solid line) light curve of V921 Her. Theoretical light curve without being contaminated by the third light is plotted with dashed line (Mode 3).

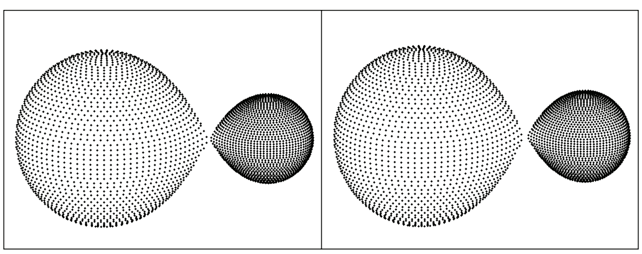

Figure 3: Geometrical structure of V921 Her at phase 0.25.

5. Discussion and Conclusions

The light curve solutions of V921 Her show that it converges at both Mode 3 and Mode 5. The solutions of Mode 3 determines a contact configuration with both of its components just filling their critical Roch lobe, and the solutions of Mode 5 determine a semidetached binary system with the secondary component filling the critical Roch lobe and the primary one filling 98% of the critical Roch lobe. However, as displayed in Table 3, the solutions between Mode 3 and Mode 5 have only very small differences in parameters such as orbital inclination i; temperature of star 2 (T_2), potential of star 1 (Ω_1) and star 2 (Ω_2), luminosity ratio of L_1/L_2, and the contribution of the third light l_3. Thus, we can conclude that V921 Her may be a marginal contact or B-type binary system [29]. The temperature difference between its two components is about 700 K, which indicates that V921 Her is a poor thermal contact binary system. It is an important target which is exactly in the rare phase predicted by the thermal relaxation oscillation (TRO) theory [30–33].

Compared with the solutions obtained by Gazeas et al. [4], we determined a much higher orbital inclination and our temperature for star 2 is about 300 K lower than theirs, which may be due to the different mass ratio ($q = 0.226$) we used. And also, we add a third light in our solutions, which may also account for these differences. As we conclude that V921 Her is a marginal contact binary system and being on the TRO stage, it is not so strange that a contact configuration was obtained by Gazeas et al. [4].

Table 4: Absolute parameters of the two components in V921 Her.

Parameters	Primary	Secondary
M	$1.784\ (\pm 0.055) M_\odot$	$0.403\ (\pm 0.012) M_\odot$
R	$2.56\ (\pm 0.38) R_\odot$	$1.29\ (\pm 0.19) R_\odot$
L	$12.2\ (\pm 1.5) L_\odot$	$1.59\ (\pm 0.20) L_\odot$

Notes: the absolute physical parameters are calculated according to the solutions of Mode 3.

Considering the orbital inclination ($i = 75^\circ$) of ours and the mass function given by Rucinski et al. [3], $(M_1 + M_2)\sin^3 i = 1.971 \pm 0.061 M_\odot$, we can easily calculate the mass of the two components to be $M_1 = 1.784\ (\pm 0.055) M_\odot$, $M_2 = 0.403\ (\pm 0.012) M_\odot$. And the orbital semimajor axis is obtained to be $a = 5.00\ (\pm 0.15) R_\odot$. The absolute physical parameters of the two components in V921 Her are listed in Table 4. The absolute physical parameters are calculated according to the solutions of Mode 3. It is almost the same with the values calculated by using the solutions of Mode 5 since they give out nearly equal surface temperature, orbital inclination, and so on.

As discussed by Liao and Qian [34], the most plausible explanation of the cyclic period changes in close binaries is the light-travel time effect (LTTE) caused by the presence of the tertiary component around the binary system. By assuming a circular orbit ($e = 0.0$), the projected radius of the orbit that the eclipsing binary rotates around the barycenter of the triple system is calculated with the following equation,

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

where A_3 is the amplitude of the $O-C$ oscillation and c is the speed of light; that is, $a'_{12} \sin i' = 0.89\ (\pm 0.03)$ AU. The mass function is computed with the following equation:

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

where G and P_3 are the gravitational constant and the period of the $(O-C)_2$ oscillation. Thus, we obtain the mass function to be $f(m) = 0.007 M_\odot$. The relationship between the orbital inclination (i') and the mass (M_3) of the tertiary component is plotted in Figure 4(a). The relationship between the orbital inclination (i') and orbital radius (a_3) of the tertiary component is also plotted in Figure 4(b).

D'Angelo et al. [35] and Pribulla and Ruciński [36] pointed out that most overcontact binaries existed in multiple systems. A survey of 165 solar-type spectroscopic binaries concluded that the fraction of spectroscopic binaries with additional companions reached 96% for $P < 3$ d [37]. As for V921 Her, both light curve solutions and $O-C$ fitting results confirm the existence of a close-in tertiary component orbiting around the binary system. As shown in Figure 2, the third light significantly reduces the depth of the eclipse occultation. According to our results, the luminosity of the third component (L_3) is nearly twice the luminosity

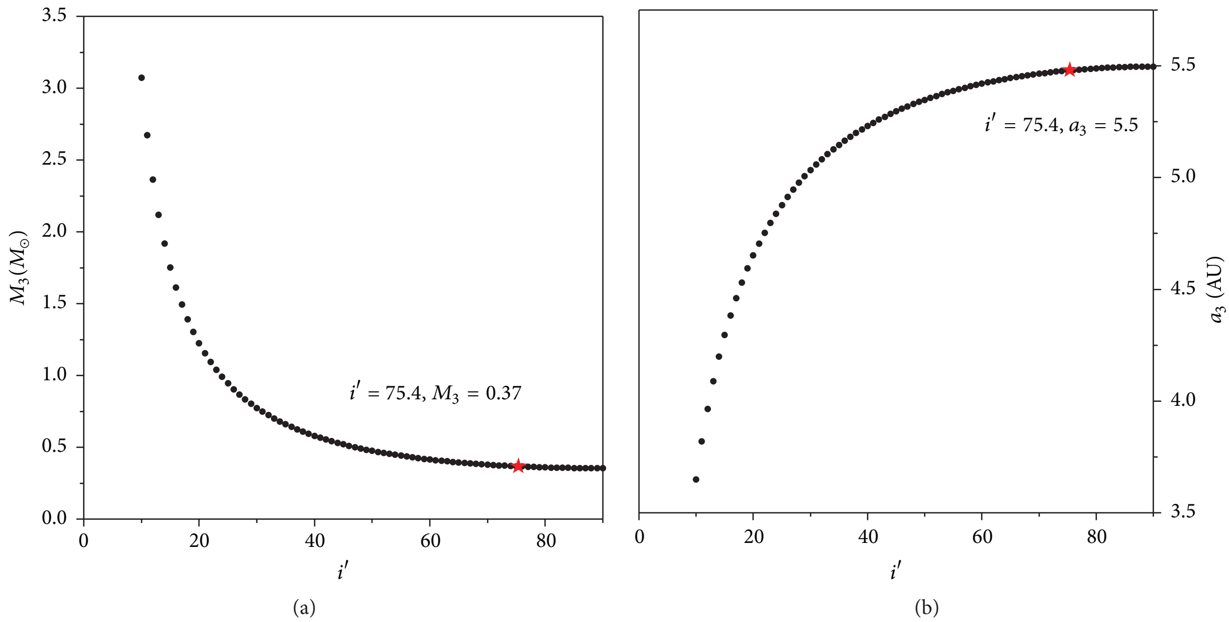

FIGURE 4: The relationship between i' and M_3 (a). The relationship between i' and a_3 (b).

of the secondary star (L_2). It is a stellar component which contributes about 19% of the total luminosity in the triple system. It is supposed that the presence of a third component has played an important role in the formation and evolution of V921 Her by removing angular momentum from the central binary system during the early dynamical interaction [38].

The $O - C$ analysis also shows that the orbital period of V921 Her is increasing at a rate of $dP/dt = 2.79 \times 10^{-7}$ day · year^{-1}. By considering a conservative mass transfer and combining the estimated mass of V921 Her with the well-known equation

$$\frac{dM_2}{dt} = \frac{M_1 M_2}{3p(M_1 - M_2)} \times \frac{dp}{dt}, \quad (7)$$

the mass transfer from the less massive component to the more massive one, at a rate of $dM_2/dt = 5.52 \times 10^{-8} M_\odot$/year, is determined.

V921 Her is under the key evolutionary stage predicted by the thermal relaxation oscillation (TRO) theory, which may evolve into a contact binary system. It is a very interesting target for testing theoretical scenario of formation and evolution on W UMa type binaries. More photometric and spectroscopic observations are still needed in the future. This object will be monitored for a long time.

Competing Interests

The authors declare that they have no competing interests.

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