PHOTOMETRIC AND PERIOD INVESTIGATION OF THE LATE F-TYPE OVERCONTACT BINARY II UMa

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ABSTRACT

II UMa is a late F-type (F5) contact binary with a close-in tertiary and a distant visual companion. According to the four-color (B V R I) light curves’ solutions of II UMa, it is a high fill-out (f = 86.6%) and low-mass ratio (q = 0.172) contact binary system, which indicates that it is at the late evolutionary stage of late-type tidal-locked binary stars. The masses of the primary star and secondary star are calculated to be \( M_1 = 1.99 M_\odot \) and \( M_2 = 0.34 M_\odot \). The primary star has evolved from the zero-age main sequence, but it still appeared before the terminal-age main sequence, and the secondary star is even more evolved. Considering the mass ratio (\( M_2/M_1 = 0.67 \)) obtained by spectroscopic observations, the mass of the close-in tertiary is estimated to be \( M_3 = 1.34 M_\odot \). The period variations of the binary system are investigated for the first time. According to the observed–calculated (O–C) curve analysis, a continuous period increase at a rate of \( dp/dt = 4.88 \times 10^{-7} \) day yr\(^{-1} \) is determined. The parabolic variation in the O–C curve may be part of a cyclic period of change, or the combined period of change of a parabolic variation and a cyclic one. More instances of minimum light are needed to confirm this. The presence of the tertiary component may play an important role in the formation and evolution of this binary system by drawing angular momentum from the central system during the pre-contact stage.

Key words: binaries: close – binaries: eclipsing – stars: evolution – stars: individual (II UMa)

1. INTRODUCTION

W UMa-type binaries are cool, short-period (usually less than one day) binary systems with both components filling their critical Roche lobes and sharing a common convective envelope during their main-sequence (MS) evolutionary stages. The more massive primary component is an MS star, whereas the secondary is oversized compared to its expected MS radius. The formation and evolution of W UMa-type binary systems are still unsolved problems in astrophysics. The most popular evolutionary scenario is that they are formed from initially detached systems via angular momentum loss (AML) by means of magnetic stellar wind (Vilhu 1982; Eggen & Iben 1989). Model calculations suggest that these binary stars will ultimately coalesce into single stars, which may be progenitors of the poorly understood blue stragglers and FK Com-type stars (Stepienni 2006, 2011).

II UMa (BD+55 1540, HIP 61237, \( V = 8.5 - 48 \)) is a component of the visual binary ADS 8954, with a separation of 0\(^\prime\)87 and a difference in brightness of 1.64 mag. The photometric variability of the star was discovered by the Hipparcos satellite (ESA, 1997). Radial velocity curves of both components in II UMa were obtained by Rucinski et al. (2002) and gave the following results: \( q = 0.172 \pm 0.004 \), \( \varv = -8.02 \pm 1.10 \) km s\(^{-1}\), \( (M_1 + M_2) \sin^2 i = 2.180 \pm 0.080 M_\odot \). They pointed out that II UMa was an A-subtype W UMa binary system with a spectral type of F5III. Later, a detailed investigation by D’Angelo et al. (2006) determined that it was a triple system with a solar-type close-in tertiary component. The temperature of the tertiary component is about 6100 K and the mass ratio is \( M_3/M_1 = 0.67 \). The first photometric solutions of II UMa were published by Oh et al. (2007). Then, Yilmaz et al. (2015) obtained the photometric parameters of this binary system. In the present work, four-color light curves (LCs) of II UMa are analyzed and its formation and evolutionary scenario are discussed. The period variations of the binary system are investigated for the first time, which may reveal the dynamic interactions between the two components.

2. OBSERVATIONS

The four-color (B V R I) LCs of II UMa were carried out over five continuous nights on 2012 February 1, 2, 3, 4, and 5, with an Andor DV436 2 K CCD camera attached to the 60 cm reflecting telescope at Yunnan Observatories (YNOs). The coordinates of the variable star, the comparison star, and the check star were listed in Table 1. The integration times were 60 s for B band, 30 s for V band, 15 s for R band, and 10 s for I band, respectively. The LCs of those observations were displayed in Figure 1. During the observations, the broadband Johnson-Cousins B V R I filters were used. The PHOT (measured magnitudes for a list of stars) of the aperture photometry package in the IRAF\(^5\) was used to reduce the observed images.

Times of minimum light of II UMa were also observed and determined, which were listed in Table 2.

3. ORBITAL PERIOD INVESTIGATION

The study of orbital period change is very important for contact binary stars. However, the period change investigation of II UMa has been neglected since it was discovered. During the present work, all available times of minimum light are collected. Minimum times with the same epoch have been averaged, and only the mean values are listed in Table 3.

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\(^5\) The Image Reduction and Analysis Facility is Hosted by the National Optical Astronomy Observatories in Tucson, Arizona at iraf.noao.edu.
The minimum times of II UMa are listed in Table 3. Using the following linear ephemeris,

$$\text{Min.} I (\text{HJD}) = 2456030.2416 + 0^d 82522 \times E, \quad (1)$$

the $O-C$ values are calculated and listed in the fourth column of Table 3 and plotted in the upper panel of Figure 2. Based on the least-square method, the new ephemeris is

$$\text{Min.} I = 2456030.2428(\pm 0.0001)$$
$$+ 0.82522813(\pm 0.00000006) \times E$$
$$+ 0.552(\pm 0.007) \times 10^{-9} \times E^2. \quad (2)$$

With the quadratic term included in this ephemeris, a continuous period increase, at a rate of $dP/dt = 4.88 \times 10^{-7}$ day yr$^{-1}$ is determined. The residuals from Equation (2) are displayed in the lower panel of Figure 2.

4. PHOTOMETRIC SOLUTIONS

II UMa is an EW-type contact binary. The W-D program of the 2013 version (Wilson & Devinney 1971; Wilson 1979, 1990, 2008, 2012; Van Hamme & Wilson 2007; Wilson et al. 2010) is used in modeling the LCs. The number of observational data points used in the W-D program are 566 in $B$ band, 599 in $V$ band, 613 in $R_c$ band, and 633 in $I_c$ band, respectively. The phases are calculated with the following linear ephemeris.

$$\text{Min.} I (\text{HJD}) = 2456030.2416 + 0^d 82522 \times E. \quad (3)$$

According to its spectral type of F5, the effective temperature of star 1 is assumed to be $T_1 = 6550$ K. The bolometric albedo $A_1 = A_2 = 0.5$ (Ruciniski 1969) and the values of the gravity-darkening coefficients $g_1 = g_2 = 0.32$ (Lucy 1967) are used. The bolometric and passband-specific limb-darkening coefficients are chosen from Van Hamme’s (1993) table. The adjustable parameters are (1) the orbital inclination $i$, (2) the mean temperature of star 2 ($T_2$), (3) the monochromatic luminosity of star 1 ($L_{1B}$, $L_{1V}$, $L_{1R}$ and $L_{1I}$), (4) the dimensionless potential of star 1 ($\Omega_1 = \Omega_2$ in mode 3 for overcontact configuration), and (5) the third light $l_3$. The final photometric solutions are listed in Table 4 and the theoretical LCs are displayed in Figure 3. The contact configuration of II UMa is displayed in Figure 4.

It has to be mentioned that the errors listed in Table 4 are internal errors resulting from the application of the WD code to the supplied data. The effective temperature of the primary star ($T_1$) may have some uncertainties due to the very wide spectral lines coming from the binary and the presence of the lines coming from the third body. We use the color index of II UMa to estimate the real uncertainties of $T_1$. According to the color index ($B-V = 0.447$) given by the Tycho-2 Catalog (Høg et al. 2000), the spectral type of II UMa is F5. However, the

![Figure 1](image-url)
2MASS All Sky Catalog gives the color index of $J-H = 0.189$ (Cutri et al. 2003), which corresponds to a spectral type of F3. Furthermore, the color index of $V-K = 1.089$ also supports the fact that the spectral type is F5 (Cox 2000). Thus, the effective temperature of the primary star ($T_1$) may range from 6550 to 6680 K. Solution B of $T_1 = 6680$ K is also listed in Table 4.

According to Oh et al.’s (2007) work, we also set $T_1 = 6412$ K and give Solution C in Table 4. We can conclude that Solution A, Solution B, and Solution C give almost consistent results, though $T_1$ ranges from 6412 to 6680 K.

5. DISCUSSIONS AND CONCLUSIONS

The light curves’ solutions indicate that II UMa is an overcontact binary system with a high contact degree ($f = 86.6\%$) and an extremely low-mass ratio ($q = 0.172$), which indicate that it is at the final evolutionary stage of cool short-period binaries. It may merge into a single rapid-rotation star, which may be the progenitor of a blue straggler or an FK Com-type star (Zhou et al. 2015). The two components have nearly the same surface temperature ($\Delta T = 4$ K) in spite of their different masses and radii, which indicate that the system

Table 3

| JD (Hel.) (2400000+) | Min Epoch | $(O - C)$ | Error | Method | Reference |
|--------------------|-----------|------------|--------|--------|-----------|
| 48371.7587         | II        | −9280.5    | −0.0287| 0.0014 | CCD       | 1         |
| 48372.1747         | I         | −9280      | −0.0253| 0.0016 | CCD       | 1         |
| 51221.6579         | I         | −5827      | −0.0268| 0.0044 | CCD       | 2         |
| 52649.7056         | II        | −4096.5    | −0.0223| 0.0007 | CCD       | 3         |
| 52723.5654         | I         | −4007      | −0.0197| 0.0004 | CCD       | 4         |
| 53064.3778         | I         | −3594      | −0.0231| 0.0002 | CCD       | 5         |
| 53081.7130         | I         | −3573      | −0.0176| 0.0020 | CCD       | 6         |
| 53761.2818         | II        | −2749.5    | −0.0174| ...    | CCD       | 7         |
| 53809.1465         | II        | −2691.5    | −0.0155| ...    | CCD       | 7         |
| 54528.3212         | I         | −1820      | −0.0200| ...    | CCD       | 8         |
| 55231.8365         | II        | −967.5     | −0.0048| 0.0001 | CCD       | 9         |
| 55280.5232         | II        | −908.5     | −0.0060| 0.0003 | CCD       | 10        |
| 55961.3776         | II        | −83.5      | 0.0018 | 0.0005 | CCD       | 11        |
| 55963.3963         | I         | −81        | −0.0025| 0.0005 | CCD       | 11        |
| 56030.2416         | I         | 0          | 0      | 0.0002 | CCD       | 11        |
| 56057.4753         | I         | 33         | 0.0014 | 0.0004 | CCD       | 12        |
| 56265.4368         | I         | 285        | 0.0075 | 0.0011 | CCD       | 11        |
| 56319.4864         | II        | 350.5      | 0.0052 | 0.0006 | CCD       | 12        |
| 56399.1215         | I         | 447        | 0.0066 | 0.0008 | CCD       | 11        |
| 56404.0720         | I         | 453        | 0.0057 | 0.0007 | CCD       | 11        |
| 56713.5344         | I         | 828        | 0.0106 | 0.0007 | CCD       | 12        |
| 56725.4998         | II        | 842.5      | 0.0103 | 0.0002 | CCD       | 12        |
| 56744.0597         | I         | 865        | 0.0027 | 0.0007 | CCD       | 11        |

Reference: (1) Private provision; (2) Rucinski et al. (2002), (3) Drozdz & Ogloza (2005), (4) Porowski (2005), (5) Krajci (2005), (6) Nelson (2005), (7) Nagai et al. (2007), (8) Nagai et al. (2009), (9) Dvorak (2011), (10) Brat et al. (2011), (11) present work, (12) Zasche et al. (2014).
Table 4
Photometric Solutions of II UMa

| Parameters           | Solution A         | Solution B         | Solution C         |
|----------------------|--------------------|--------------------|--------------------|
| T_1 (K)              | 6550(fixed)        | 6680(fixed)        | 6412(fixed)        |
| g_1                  | 0.32(fixed)        | 0.32(fixed)        | 0.32(fixed)        |
| g_2                  | 0.32(fixed)        | 0.32(fixed)        | 0.32(fixed)        |
| A_1                  | 0.50(fixed)        | 0.50(fixed)        | 0.50(fixed)        |
| A_2                  | 0.50(fixed)        | 0.50(fixed)        | 0.50(fixed)        |
| q (M_2/M_1)          | 0.172(fixed)       | 0.172(fixed)       | 0.172(fixed)       |
| i (°)                | 77.8(±0.3)         | 77.8(±0.3)         | 77.7(±0.3)         |
| Ω_in                 | 2.1615             | 2.1615             | 2.1615             |
| Ω_out                | 2.0511             | 2.0511             | 2.0511             |
| Ω_2 = Ω_2           | 2.0659(±0.0047)    | 2.0685(±0.0057)    | 2.0665(±0.0048)    |
| T_2 (K)              | 6554(±7)           | 6684(±8)           | 6418(±7)           |
| ΔT (K)               | 4                  | 4                  | 6                  |
| L_2/L_1              | 1.001(±0.001)      | 1.001(±0.001)      | 1.001(±0.001)      |
| L_3/(L_4 + L_2) (B)  | 0.8084(±0.0008)    | 0.8086(±0.0007)    | 0.8082(±0.0008)    |
| L_3/(L_4 + L_2) (V)  | 0.8091(±0.0010)    | 0.8092(±0.0010)    | 0.8089(±0.0010)    |
| L_3/(L_4 + L_2) (R_1)| 0.8094(±0.0015)    | 0.8095(±0.0015)    | 0.8092(±0.0015)    |
| L_3/(L_4 + L_2) (R_2)| 0.8097(±0.0030)    | 0.8097(±0.0030)    | 0.8095(±0.0030)    |
| L_3/(L_4 + L_2 + L_3) (B)| 0.2992(±0.0023) | 0.2954(±0.0023) | 0.3013(±0.0023) |
| L_3/(L_4 + L_2 + L_3) (V)| 0.2754(±0.0032) | 0.2728(±0.0032) | 0.2762(±0.0032) |
| L_3/(L_4 + L_2 + L_3) (R_1)| 0.2674(±0.0051) | 0.2648(±0.0051) | 0.2684(±0.0050) |
| L_3/(L_4 + L_2 + L_3) (R_2)| 0.2682(±0.0098) | 0.2658(±0.0098) | 0.2693(±0.0097) |
| r_1(pole)            | 0.5209(±0.0004)    | 0.5241(±0.0008)    | 0.5219(±0.0001)    |
| r_1 (side)           | 0.5790(±0.0006)    | 0.5842(±0.0014)    | 0.5807(±0.0002)    |
| r_1 (back)           | 0.6083(±0.0008)    | 0.6148(±0.0017)    | 0.6104(±0.0002)    |
| r_2(pole)            | 0.2499(±0.0005)    | 0.2512(±0.0011)    | 0.2522(±0.0002)    |
| r_2 (side)           | 0.2644(±0.0006)    | 0.2660(±0.0013)    | 0.2672(±0.0002)    |
| r_2 (back)           | 0.3424(±0.0024)    | 0.3490(±0.0057)    | 0.3546(±0.0010)    |
| f                    | 86.6%(±4.2%)       | 84.2%(±5.2%)       | 86.9%(±4.3%)       |
| Σω(O - C)^2          | 0.036625           | 0.036671           | 0.036514           |

Note. The errors listed in Table 4 are internal errors resulting from the application of the WD code to the supplied data.

Figure 3. Observed (open circles) and theoretical (solid lines) light curves in the BVR, and I bands for II UMa. The standard deviations of the fitting residuals are 0.011 mag for B band, 0.011 mag for V band, 0.010 mag for R, and 0.010 mag for I, respectively. The dashed lines represent theoretical light curves without the third light.
is under thermal contact. Considering the mass function given by Rucinski et al. (2002), \( (M_1 + M_2) \sin^2 i = 2.180 \pm 0.080 M_\odot \) and the orbital inclination \( i = 77^\circ 8 \) obtained by the LCs' solutions, the masses of the two components are calculated to be \( M_1 = 1.99(\pm 0.08) M_\odot \) and \( M_2 = 0.34(\pm 0.01) M_\odot \). The spectroscopic search carried out by D'Angelo et al. (2006) confirmed that II UMa was a triple system with a solar-type tertiary component, and determined the effective temperature of the third component to be \( T = 6100 \) K, which corresponded to a G0V-type star. The mass of the third component is estimated to be \( M_3 = 1.34(\pm 0.05) M_\odot \) according to the mass ratio \( M_3/M_1 = 0.67 \) obtained. The third light \( (I_3) \) also included as an adjustable parameter during the photometric processing. The LC solutions also confirm that it is a triple system and the third component contributes nearly a quarter of the total luminosity. As shown in Figure 3, the existence of the third light apparently reduces the occultation depth.

Spectroscopic observations show that II UMa may be a contact binary with a giant star as its primary component. It does have quite a long period \( (P = 0.82522 \text{d}) \), which does not obey the well-defined period–color relation of the contact binary. However, the parameters obtained by us show that the radius of the apparent giant is equal to about \( 2.7 R_\odot \). The \( 2M_\odot \) star should have a radius equal to about \( 3.5 R_\odot \) when it leaves MS. Thus, the primary star of II UMa has evolved from the zero-age main sequence (ZAMS), but it is still before the terminal-age main sequence (TAMS). II UMa is one of the A-type W UMa stars. Detailed modeling by Stepien (2011) concluded that initially detached binary systems will eventually evolve to MS contact binaries or Algol-type binary systems. We assume that II UMa is formed from an initially detached system via AML by means of magnetic stellar wind. It is just under the late evolutionary stage of late-type tidal-locked binary stars, which might be close to merging and evolving into a single rapid-rotating star.

II UMa is a member of a visual binary system. The close binary system is even confirmed to be a triple system with a close-in solar-type tertiary component orbiting around the close binary system. Thus, it is actually a quadruple system. As discussed by Qian et al. (2013, 2014), the existence of an additional stellar component in the binary system may play an important role in formation and evolution by removing angular momentum from the central binary system during the early dynamical interaction or late evolution. The \( O–C \) curve analysis shows a continuous period increase at a rate of \( dP/dt = 4.88 \times 10^{-7} \text{~day~yr}^{-1} \), which may be just a part of a cyclic period change, or the combinational period change of a parabolic variation and a cyclic one. More times of minimum light are needed to confirm this. II UMa is an important target for testing theories of star formation and stellar dynamical evolution and interaction. It is possible that third-body interactions in the birth environment may help to accelerate the orbital evolution of the central binary system. Angular momentum is drained from the inner close pair either by the ejection of the tertiary companion (Goodwin et al. 2004) or through the Kozai mechanism (Kozai 1962; Fabrycky & Tremaine 2007).

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