THE TRIPLY ECLIPSING HIERARCHICAL TRIPLE STAR KIC002856960

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ABSTRACT

In a recent study, Armstrong et al. presented an eclipsing binary star of about 6.2 hr period with transit-like tertiary signals occurring every 204.2 days in the Kepler public data of KIC002856960 and proposed three possible hierarchical structures: (AB)b, (ABC), and A(BC). We analyzed the Kepler light curve by including a third light source and one starspot on each binary component. The results represent that the close eclipsing pair is in a low-mass eccentric-orbit, detached configuration. Based on 123 eclipse timings calculated from the Wilson–Devinney binary model, a period study of the close binary reveals that the orbital period has experienced a sinusoidal variation with a period and a semi-amplitude of $205 \pm 2$ days and $0.0021 \pm 0.0002$ days, respectively. The period variation would be produced by the light-travel-time effect due to a gravitationally bound third body with a minimum mass of $M_3 \sin i_3 = 0.76 M_\odot$ in an eccentric orbit of $e_3 = 0.61$. This is consistent with the presence of third light found in our light curve solution and the tertiary signal of 204.2 day period most likely arises from the K-type star crossed by the close eclipsing binary. Then, KIC002856960 is a triply eclipsing hierarchical system, A(BC), consisting of a close binary with two M-type dwarfs and a more massive K-type component. The presence of the third star may have played an important role in the formation and evolution of the close pair, which may ultimately evolve into a contact system by angular momentum loss.

Key words: binaries: close – binaries: eclipsing – stars: individual (KIC002856960) – starspots

Online-only material: color figure

1. INTRODUCTION

Multiple star systems with eclipsing features are very rare and interesting objects for understanding the star formation and stellar dynamical evolution. To our knowledge, four systems have been found to be a double eclipsing binary (ADS 9537AB, Batten & Hardie 1965; V994 Her, Lee et al. 2008a; KIC 4247791, Lehmann et al. 2012; CzeV343, Cagaš & Pejcha 2012) and two systems to be a triply eclipsing hierarchical triple (HD 181068, Derekas et al. 2011; KOI-126, Carter et al. 2011). In the case of hierarchical triple star systems (double+single), the outer third components may remove angular momentum from the inner close pairs via Kozai oscillation (Kozai 1962; Pribulla & Rucinski 2006) or a combination of the Kozai cycle and tidal friction (Fabrycky & Tremaine 2007). Kozai cycles periodically raise the eccentricity of the close binary, while the tidal friction efficiently dissipates the orbital energy during the close pericenter passages. As a result, the inner close binary undergoes an orbital period decrease and forms the tidal-locked detached binary with a short orbital period.

The presence of a third body orbiting an eclipsing binary causes a periodic variation of the eclipsing period due to the increasing and decreasing light-travel times (LTT) to the observer (Irwin 1952, 1959). The timing variability may be represented by an $O–C$ diagram, showing the differences between the observed ($O$) and the calculated ($C$) eclipse epochs. Because times of minimum light act as an accurate clock, they have been used as a tool that detects the third components to close binary stars. With timing accuracies of about $\pm 10$ s, it should be possible to detect circumbinary planets of $\sim 10 M_{\text{Jup}}$ in longer periods around eclipsing systems (Ribas 2006; Lee et al. 2009; Pribulla et al. 2012).

In a recent work, Armstrong et al. (2012) reported a very interesting discovery of an eclipsing binary star with tertiary signals in the Kepler public data of KIC002856960 (R.A.2000 = 19°29′31″52; decl.2000 = +38°04′35″39; $K_p = +15.615$; $T_{\text{eff}} = 4733$ K). The close binary components display eclipses with a 6.2 hr (0.2585 days) period, while the outer third body leads to transit-like features in the light curve occurring every 204.2 days. They suggested that the tertiary signals may result from either a planetary companion (or low-mass dwarf star) orbiting around a close eclipsing binary, (AB)b/C, or a close binary orbiting around a more massive star, A(BC) (named C(AB) in their paper), but were unable to distinguish between them. In this paper, we analyze in detail the light curve and eclipse timings from the Kepler photometric data, and show that KIC002856960 has evidences of a triple star system, consisting of a close binary and a more massive third companion forming a wider binary with the mass center of the close pair.

2. KEPLER LIGHT-CURVE ANALYSIS

For our study, we used 22,695 individual observations (BJD 2454964–2455462) from the first six quarters of Kepler operations. Detailed information about the Kepler spacecraft and its performance can be found in Koch et al. (2010). The light curve of KIC002856960 is plotted in Figure 1, as normalized flux versus orbital phase, which was computed according to the linear terms of the LTT ephemeris described in the following section. In order to determine the photometric solutions of the binary pair, the Kepler data were analyzed by using the 2003 version of the Wilson–Devinney synthesis code (Wilson & Devinney 1971, hereafter W-D). For this purpose, the mean light level at phase 0.70 was set to unity. The logarithmic bolometric ($X$, $Y$) and monochromatic ($x$, $y$) limb-darkening coefficient were interpolated from the values of van Hamme (1993) in concert with the model atmosphere option. The gravity-darkening exponents and bolometric albedoes were held fixed at standard values.
(g = 0.32 and A = 0.5) for stars with convective envelopes. A mass ratio of q = 1.0 and a circular orbit (e = 0.0) were initially taken from visual inspection of the light curve and a synchronous rotation for both components was adopted. Furthermore, a third light source (ℓ3) was considered. In Table 1, the parameters with parenthesized formal errors signify the adjusted ones and the subscripts 1 and 2 refer to the primary and secondary stars being eclipsed at Min I and Min II, respectively.

The effective temperature of KIC002856960 is given as 4733 K from Kepler Input Catalogue (KIC; Brown et al. 2011), which would correspond to a spectral type of approximately K3. First of all, we analyzed the Kepler data by adopting this value as a temperature of the primary component. The preliminary analysis reveals ℓ1 to contribute about 97% to the total luminosity of this system. This indicates that the KIC temperature might mainly come from the third component and then that the close binary may be composed of two M-type components. Thus, the surface temperature of the hotter primary star was initialized to be T1 = 3150 K.

Our light-curve analyses have been performed through three stages. In the first stage, the light curve was solved without spots. The result for this unspotted model is plotted as the dashed curve in Figure 1, where the computed light curves do not fit well with the Kepler data. This discrepancy in low-mass close binaries can be explained by spot activity on binary components as a magnetic dynamo effect (e.g., Lee et al. 2012).

In the second stage, we analyzed the light curve by using the unspotted solution as the initial values and including the starspot on the component stars. The result for the spot model is given as Model 1 in Table 1 and displayed as the solid curves in Figure 1. The light variation was satisfactorily modeled by using the synthetic curves obtained from no spot and the two-spot model, respectively. Fifty-three data points out of the flux range between 0.975 and 1.010 are not plotted to see in detail the eclipsing light curve.

(A color version of this figure is available in the online journal.)

![Figure 1](image)

**Figure 1.** Light curve of KIC002856960 with the fitted models. The circles are individual measures from the Kepler spacecraft and the dashed and solid lines represent the synthetic curves obtained from no spot and the two-spot model, respectively. Fifty-three data points out of the flux range between 0.975 and 1.010 are not plotted to see in detail the eclipsing light curve.

**Table 1.** Close Binary Parameters of KIC002856960

| Parameter | Model 1 | Model 2 |
|-----------|---------|---------|
| q         | 1.0     | 1.006(82) |
| e         | 0.0     | 0.006(14) |
| ω0 (deg)  | 85.32(88) | 161(26) |
| i (deg)   | 5.93(11) | 5.87(11) |
| T (K)     | 3153(160) | 3160(150) |
| Ω         | 3.75     | 3.92     |
| A         | 0.5      | 0.5      |
| g         | 0.32     | 0.32     |
| X, Y      | 0.485, 0.276 | 0.485, 0.276 |
| x, y      | 0.748, 0.255 | 0.748, 0.255 |
| r (pole)  | 0.2021(43) | 0.2093(60) |
| r (point) | 0.2070(47) | 0.2157(71) |
| r (side)  | 0.2038(44) | 0.2114(63) |
| r (back)  | 0.2062(46) | 0.2145(68) |
| r (volume) | 0.2041 | 0.2118 |
| Spot parameters: |
| Colatitude (deg) | 39.2(2.3) | 39.2(2.6) |
| Longitude (deg)  | 354.8(2.2) | 265.1(2.2) |
| Radius (deg)     | 38.2(1.4) | 38.2(1.4) |
| T_{spot}/T_{bloc} | 0.850(11) | 0.853(9) |
| ΣW(O − C)²     | 0.0101   | 0.0090   |

**Notes.**

* Value at 0.70 phase.
* Mean volume radius.

The period and duration of the tertiary signal were estimated to be about 204.2 days and 1.3 days and its maximum depth is 6.8% to the system flux, which is about six times deeper than the close binary eclipse. These values are almost consistent with those given by Armstrong et al. (2012).
Figure 2. Light residuals corresponding to Model 2 listed in Table 1. The tertiary signals are plotted in the lower three panels, wherein the vertical dotted lines indicate the primary eclipse times of the close pair predicted from our LTT ephemeris.

Figure 3. Kepler data of KIC002856960 combined at the intervals of 15 orbital periods. The eclipse timing variations are evident visually from the light curves offset from 1.0.

but the light residuals from the W-D binary model presented in this paper may be more reasonable to resolve the tertiary signal to the Kepler data.

Assuming the primary star to be a normal main-sequence one with a spectral type of about M6, we estimated the absolute dimensions for Model 1 and Model 2 from our photometric solutions and from Harmanec’s (1988) relation between the spectral type (effective temperature) and stellar mass. These are given in the entries on the last three lines of Table 1. The radii are the mean volume radii calculated from the tables of Mochnacki (1984) and the luminosity ($L$) was computed by adopting $T_{\text{eff,\odot}} = 5780$ K and $M_{\text{bol,\odot}} = +4.73$ for solar values.
| BJD   | Error   | $E$       | $O-C_{\text{full}}$ |
|-------|---------|-----------|---------------------|
| 245496.78685 | ±0.00031 | 0         | -0.000095           |
| 245496.66495 | ±0.00027 | 15        | +0.000475           |
| 245497.54245 | ±0.00026 | 30        | +0.000429           |
| 245497.41969 | ±0.00032 | 45        | +0.000102           |
| 245498.29760 | ±0.00031 | 60        | +0.000418           |
| 245498.17471 | ±0.00062 | 75        | -0.000100           |
| 245498.05220 | ±0.00036 | 90        | -0.000282           |
| 245499.12972 | ±0.00057 | 105       | -0.000495           |
| 245500.80807 | ±0.00038 | 120       |                     |
| 245503.04867 | ±0.00141 | 148       |                     |
| 245503.56380 | ±0.00031 | 150       | -0.000232           |
| 245507.44252 | ±0.00032 | 165       | +0.000282           |
| 245511.32069 | ±0.00039 | 180       | +0.000213           |
| 245517.00905 | ±0.00154 | 202       |                     |
| 245519.07687 | ±0.00044 | 210       | +0.000210           |
| 245520.95433 | ±0.00029 | 225       | +0.000251           |
| 245526.83218 | ±0.00043 | 240       | -0.000236           |
| 245530.70975 | ±0.00035 | 255       | -0.000437           |
| 245534.85780 | ±0.00051 | 270       | -0.000106           |
| 245538.46528 | ±0.00058 | 285       | -0.000306           |
| 245542.34357 | ±0.00039 | 300       | +0.000338           |
| 245546.22161 | ±0.00055 | 315       | +0.000758           |
| 245550.09918 | ±0.00053 | 330       | +0.000731           |
| 245553.97596 | ±0.00035 | 345       | -0.000068           |
| 245557.85377 | ±0.00040 | 360       | +0.000180           |
| 245561.73124 | ±0.00043 | 375       | +0.000102           |
| 245565.60838 | ±0.00031 | 390       | -0.000293           |
| 245569.48510 | ±0.00029 | 405       | -0.001098           |
| 245573.36378 | ±0.00049 | 420       | +0.000066           |
| 245577.24146 | ±0.00049 | 435       | +0.000238           |
| 245581.11779 | ±0.00055 | 450       | -0.000932           |
| 245584.99559 | ±0.00065 | 465       | -0.000826           |
| 245589.64915 | ±0.00055 | 483       | -0.000051           |
| 245593.52721 | ±0.00037 | 498       | +0.000527           |
| 245596.62844 | ±0.00029 | 510       | -0.000026           |
| 245600.76484 | ±0.00045 | 526       | +0.000201           |
| 245604.38364 | ±0.00031 | 540       | +0.000027           |
| 245610.26103 | ±0.00025 | 555       | -0.000552           |
| 245612.13818 | ±0.00033 | 570       | -0.000370           |
| 245616.01618 | ±0.00033 | 585       | +0.000165           |
| 245619.89316 | ±0.00038 | 600       | -0.000320           |
| 245624.54562 | ±0.00052 | 618       | -0.000817           |
| 245627.64860 | ±0.00039 | 630       | +0.000192           |
| 245631.52561 | ±0.00030 | 645       | -0.000263           |
| 245635.40340 | ±0.00040 | 660       | +0.000152           |
| 245639.28022 | ±0.00039 | 675       | -0.000586           |
| 245643.15848 | ±0.00028 | 690       | +0.000204           |
| 245647.03603 | ±0.00033 | 705       | +0.000281           |
| 245650.91372 | ±0.00033 | 720       | +0.000494           |
| 245656.85890 | ±0.00063 | 743       | +0.000199           |
| 245658.66863 | ±0.00063 | 750       | +0.000433           |
| 245662.54633 | ±0.00035 | 765       | +0.000637           |
| 245666.42271 | ±0.00032 | 780       | -0.000488           |
| 245670.30081 | ±0.00036 | 795       | +0.000095           |
| 245674.17830 | ±0.00037 | 810       | +0.000555           |
| 245678.05523 | ±0.00047 | 825       | -0.000563           |
| 245681.93463 | ±0.00122 | 840       |                     |
| 245685.81061 | ±0.00041 | 855       | -0.000348           |
| 245689.68853 | ±0.00044 | 870       | -0.000059           |
| 245693.56649 | ±0.00060 | 885       | +0.000225           |
| 245697.44446 | ±0.00035 | 900       | +0.000457           |
| 245701.32484 | ±0.00036 | 915       | +0.000226           |
| 245705.19990 | ±0.00038 | 930       | +0.000048           |
| 245709.07744 | ±0.00033 | 945       | -0.000408           |
| 245712.95618 | ±0.00038 | 960       | +0.000118           |
a total of 129 light curves. Then, the times of minimum light intervals of 15 orbital periods (15
each eclipse curve. Thus, we combined the of 29.4 minutes, corresponding to about 8% of the close binary
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effect due to the existence of a third body. Thus, we fitted the eclipse timings to the following LTT ephemeris:

Because the Kepler data were taken in long cadence mode of 29.4 minutes, corresponding to about 8% of the close binary orbital period, it is impossible to measure a minimum epoch for each eclipse curve. Thus, we combined the Kepler data at the intervals of 15 orbital periods (15 × P = 3.8775 days) and made a total of 129 light curves. Then, the times of minimum light for the separate data sets were calculated by means of adjusting only the ephemeris epoch (T₀) in the Model 2 of Table 1, and the results are listed in Table 2. As an example, 12 data sets of them are displayed in Figure 3, where the eclipse timing variations are evident from the light curves. For the ephemeris computations, we used 123 minimum epochs except for six timings, based on tertiary signals and insufficient data caused by gaps between quarters. Weights were calculated as the inverse squares of the timing errors and were then scaled from the standard deviations (σ = 0.00036 days).

As the first step, we applied a periodogram analysis to the timing data using the PERIOD04 program (Lenz & Breger 2005). The result is plotted in the upper panel of Figure 4, which shows a peak frequency at f = 0.00497 cycle day⁻¹ with a semi-amplitude of about 0.002 days. The observed frequency becomes a period of 201 days and can be interpreted as the LTT period and a deep convective envelope (Feiden & Chaboyer 2011; Torres 2012). The primary eclipse times of the close binary calculated from the LTT ephemeris are given as the dashed vertical lines in the lower panels of Figure 2. We can see that the deeper observed transits lie between the predicted timings. In the tertiary signals, the close binary passes across the disk of the K-type star. Then, the eclipsing pair partially blocks the surface of the larger and more massive star, so the brightness of the triple system becomes slightly faint. The light variation depth is proportional to the blocking area. Thus, the deeper transits may be produced when both binary components is displayed to observer, rather than when one of the two is in front of the K-type star. On the other hand, the mid-eclipse times (hereafter tertiary secondary eclipse) of the close pair eclipsed by the K-type star were estimated to be BJ 2455020.886, 2455225.101, and 245429.316 using the parameters (e₂ = 0.61 and ω₃ = 173°) of the LTT orbit. We looked for a possible eclipse/ transit around the computed times but detected no

### Table 3: Parameters for the LTT Orbits of KIC002856960

| Parameter | Value | Unit |
|-----------|-------|------|
| T₀        | 2,454,964.78879(14) | BJD |
| P         | 0.25850790(12) | days |
| aₙ sin iₙ | 0.453(41) | au |
| ωₙ        | 353(4) | deg |
| eₙ        | 0.612(82) | |
| nₙ        | 1.754(16) | deg day⁻¹ |
| Tₚ        | 2,455,007.5(2.5) | BJD |
| Pₚ        | 205.2(1.9) | days |
| Kₚ        | 0.00208(19) | days |
| f(Mₚ)     | 0.295(26) | M⊙ |
| M₁ sin i₁² | 0.760(55) | M⊙ |
| a₁ sin i₁² | 0.274(10) | au |
| ω₁        | 173(4) | deg |
| e₁        | 0.612(82) | |
| P₁        | 205.2(1.9) | days |
| χ₁²       | 1.059 | |

Note. a M₁ + M₂ = 0.46 M⊙ is assumed.

3. ECLIPSE TIMING VARIATION

Our results from both the light curve and the eclipsing timings represent that KIC002856960 is a triple star system, (A(BC), which comprises a low-mass detached close binary (BC) with a period of 0.2585 days and a more massive star (A) with an LTT period of about 205 days. The tertiary signals of 204.2 days period detected by Armstrong et al. (2012) and confirmed in this paper most likely arise from a K-type third star crossed by the close eclipsing binary with two M-type dwarfs. Then, KIC002856960 is a third member of the triple eclipsing hierarchical systems and contains the most compact close binary with the period ratio of PₐBC/Pₚₐ ≥ 790. As in the cases of KOI-126 (Carter et al. 2011) and HD 181068 (Derekas et al. 2011; Borkovits et al. 2012), the wide, single star of this system is the most massive and luminous component. The close binary stars in KIC002856960 are thought to have masses low enough to become fully convective and radii larger than predicted by stellar models, where the secondary component is oversized by about 60%. The discrepancy may be mainly caused by the effect of magnetic activity in the close binary pair with both a short period and a deep convective envelope (Feiden & Chaboyer 2012; Torres 2012).

from the complete ephemeris. These appear as O−C residual in the fourth column of Table 2. In case that the LTT period is very short, the eclipse timing variations could be partly caused by the perturbative effect of the third component added to the geometrical LTT effect (Borkovits et al. 2011; Borkovits et al. 2012). We computed the semi-amplitude of the dynamic perturbation on the motion of the close pair to be about 0.00003 days and found that its contribution is not significant.

The LTT orbit has a period of Pₚ = 205.2 days, a semi-

4. DISCUSSION AND CONCLUSIONS

The primary eclipse times of the close binary calculated from the LTT ephemeris are given as the dashed vertical lines in the lower panels of Figure 2. We can see that the deeper observed transits lie between the predicted timings. In the tertiary signals, the close binary passes across the disk of the K-type star. Then, the eclipsing pair partially blocks the surface of the larger and more massive star, so the brightness of the triple system becomes slightly faint. The light variation depth is proportional to the blocking area. Thus, the deeper transits may be produced when both binary components is displayed to observer, rather than when one of the two is in front of the K-type star. On the other hand, the mid-eclipse times (hereafter tertiary secondary eclipse) of the close pair eclipsed by the K-type star were estimated to be BJ 2455020.886, 2455225.101, and 245429.316 using the parameters (e₂ = 0.61 and ω₃ = 173°) of the LTT orbit. We looked for a possible eclipse/transit around the computed times but detected no
signals. This may be a result of the fact that the tertiary secondary eclipse is much shallower than its primary eclipse (the K-type star crossed by the close pair).

In close binaries that have tidal forces strong enough to cause synchronization of components, the orbital angular momentum is tidally coupled to the spin angular momentum. In order for the spin–orbit coupling to work efficiently, the initial orbital periods should be short \((P \lesssim 5.0\) days; Bradstreet & Guinan 1994; Pribulla & Rucinski 2006; Lee et al. 2008b). Star formation in a triple system may alleviate the close-binary formation difficulty by re-distributing most of the angular momentum of a close binary to the more distant component and by leaving a low angular momentum remnant with a short initial orbital period.

The more massive third component in KIC002856960 may have played an important role in the formation and evolution of the close pair, which would cause it to evolve into a contact configuration by angular momentum loss via magnetic braking and ultimately to coalesce into a single rapid-rotating star.

The triply eclipsing nature would clearly make KIC002856960 an ideal target for dynamical evolutionary studies and for testing tidal friction theories in hierarchical triple systems. Future high-resolution spectroscopy and follow-up photometry of tertiary signals will help reveal more accurate properties such as the absolute dimensions and evolutionary status of the triple system.

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