Kepler-TESS light curve analysis of KIC 10417986 as a practical example for astronomical research in schools

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Abstract. Teachers and students in schools have been struggled to accomplish astronomical researches themselves in Thailand, but lacked off equipment and method. The aim of this paper is to provide methods to determine physical parameters of a given Kepler eclipsing binary, without any radial velocity curves, as an example for possible school projects. Unpublished light curves of KIC 10417986 from Kepler and TESS online archives were analysed simultaneously by using the Wilson & Devinney code to derived relative photometric parameters. On an assumption of the system is a contact binary system whose components are main-sequence stars, absolute dimensions including $T_1 = 6751 \pm 900$ K, $T_2 = 6804 \pm 907$ K, $R_1 = 1.48 \pm 0.05 R_\odot$, $R_2 = 1.4 \pm 0.3 R_\odot$, $M_1 = 1.64 \pm 0.07 M_\odot$, $M_2 = 1.6 \pm 0.4 M_\odot$, and $L_1 \sim L_2 \sim 4L_\odot$, were determined. The semi-major axis $a = 3.7 \pm 0.4 R_\odot$ and a mass ratio $q = 1.0 \pm 0.2$ were calculate tracing backward from the derived dimensions. We found that such a very short period ($0^d.073731$) KIC 10417986 might not play such a good example for school project due to its very low amplitude of variation in light curves (~0.0007 magnitude) even one may conclude it is not a variable star. However, we found the system interesting since it might have high mass transfer rate from the primary onto the secondary star.

1. Introduction

School teachers and students in Thailand have been struggled to accomplish astronomical researches themselves in Thailand, but lacked off equipment and method. The aim of this paper is to propose one example that capable in schools simply by extracting data from the available online archives. The analysis of light curves of eclipsing binary stars (EBs) is picked out here as an example due to two major reasons. First, the population of binary stars occupying nearly half of all stars in the sky can stimulate students to learn astronomy. Second, the advantages of investigating EBs allowing us to determine the physical parameters of each component stars can encourage students to pursue their research in schools and probably to publications.

Approximately 4000 EBs have been discovered up to 1990 in our Galaxy [1]. For outside galaxies, several thousands of EBs has been discovered in SMC [2-3], LMC [4-5], and M31 for the last twenty
years. A vast amount of EBs light curves has become available as a by-product of the survey observations such as OGLE, EROS, and MACHO [6]. Recently, the NASA Kepler Mission, launched in 2009 March, provided essentially uninterrupted, ultra-high precision photometric light curves of ~200,000 objects which has revolutionized the exoplanetary and EBs field [7]. Although a large number of EBs have been discovered, the number of light curves analysis has still been carried out much far little compared to those discovered [6]. The major reason is the time consuming of the work and therefore it should be encouraged in schools.

The analyses of light curves and radial velocity curves of EBs can provide absolute dimensions of the stars such as masses, radii, shapes, temperatures, and luminosities of component stars in MKS units, regardless of the distances of the binaries from us [8]. The luminosity of component stars in EBs are determined directly so that EBs can be used as excellent standard candles for distance determinations among nearby galaxies [9-10]. By studying these curves, a great deal of basic astrophysical quantities can be determined, studied and discussed in schools.

Although this work is conducted by university students (CRRU undergraduates), it can be carried out as a school research since the Kepler data is available via online archives and the EBs curve fitting programme such as Wilson & Devinney code (WD) and PHOEBE are free-downloaded online.

In this study, the unpublished light curves of short-period EB KIC 10417986 from the Kepler online archives were collected and analysed by using the WD to gain relative physical parameters including radii, shapes, temperatures, and luminosities, of each component stars. The method to estimate absolute temperature, radii, masses were provided despite the absence of radial velocity curves.

2. Data acquisition and observation
Unpublished light curves of KIC 10417986 ($\alpha = 19h46m59.70s$, $\delta = +47\degree32´37.71´´$ J2000) were collected from the Kepler Eclipsing Binary Catalog during $BJD_{2455372.46992 - 2455462.29666}$ (with a very short period of 0.073731, $BJD_0 = 55000.027476 \pm 0.004231$ and $m_{Kepler} = 9.128$) and from the Transiting Exoplanet Survey Satellite (TESS) space telescope during $BJD = 2458737.4115$. Information of neither colour nor temperature were absent in [11].

Photometric observations in $B$ and $V$ filters were carried out at the Regional Observatory for Public, Songkhla, Thailand during 30-31 July 2019. We found the average magnitude $B = 9.028 \pm 0.007$, $V = 9.2 \pm 0.7$, and $B-V = -0.1 \pm 0.7$ as a result. The $J-H = 0.0940 \pm 0.018$ from 2MASS was also collected.

3. Light curves analysis
Light curves from Kepler and TESS were first analysed separately by the Wilson & Devinney synthetic programme (WD) to correct the phase-shift of each light curve. Then they were analysed simultaneously by WD in Mode 5 for a contact binary. Figure 1 shows observations with adjusted model light curves from Kepler (opened black circles fitted by a white dash line) and TESS (gray dots fitted by a black solid line). Their relative photometric elements including inclination ($i$), temperatures ($T_1$, $T_2$), potentials ($\Omega_1$, $\Omega_2$), limb darkening coefficients ($x_1$, $x_2$), gravitational darkening coefficients ($g_1$, $g_2$), reflection albedos ($A_1$, $A_2$), and Roche lobe radii ($r_1$, $r_2$) are presented in table 1.

4. The binary system temperature determination

4.1. Method 1: on an assumption of the main-sequence stars.
If we assumed the component stars to be both in the main-sequence, the effective temperature of the system ($T_{sys}$) can be derived as an effective temperature ($T_{eff}$) by using the relation between colour index $J-H$ and temperature calibrated for FGK dwarf stars given by [12]

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1 ASAS-SN Variable Stars Database
2 Available online at https://irsa.ipac.caltech.edu/
\[ T_{\text{eff}} = -4369.5(J - H) + 7188.2 \]  

which is valid over the approximate temperature range $4000 < T_{\text{eff}} < 7000$ K. The 2MASS $J - H = 0.0940 \pm 0.018$ of KIC 10417986 yielded $T_{\text{sys}} = T_{\text{eff}} = 6777 \pm 157$ K as a result.

**Figure 1.** The observations with adjusted model light curves from Kepler (opened black circles fitted by a white dash line) and TESS (gray dots fitted by a black solid line) as results of parameters presented in table 1.

| Parameters                  | Solution          | Kepler       | TESS        |
|-----------------------------|-------------------|--------------|-------------|
| $i$ (degree)                |                   | 2.563±0.003  | 5.56±0.03   |
| $\Omega_1$                  |                   | 3.5537±0.0004 | 5.40±0.04   |
| $\Omega_2$                  |                   | 3.5537      | 5.40±0.04   |
| $T_1$ (K)                   |                   | 6015±44      | 6058        |
| $T_2$ (K)                   |                   | 6058        |             |
| $L_1$                       |                   | 5.51±0.03    | 5.56±0.03   |
| $L_2$                       |                   | 5.39±0.04    | 5.40±0.04   |
| $A_1$                       |                   | 0.403±0.005  |             |
| $A_2$                       |                   | 0.440±0.005  |             |
| $g_1$                       |                   | 0.229±0.003  |             |
| $g_2$                       |                   | 0.243±0.003  |             |
| $\chi_1$                    |                   | 0.293±0.003  | 0.532±0.003 |
| $\chi_2$                    |                   | 0.306±0.003  | 0.553±0.1   |
| $r_1$ pole                  |                   | 0.3746±0.001 |             |
| $r_1$ side                  |                   | 0.3964±0.001 |             |
| $r_1$ back                  |                   | 0.4347±0.001 |             |
| $r_2$ pole                  |                   | 0.3653±0.001 |             |
| $r_2$ side                  |                   | 0.3859±0.0001|             |
| $r_2$ back                  |                   | 0.4249±0.0001|             |
4.2. Method 2 : on an assumption of the nearby-stars

The effective temperature of the system \( T_{\text{sys}} \) can also be derived by using the relation between colour index \( B-V \) and temperature derived by this study. We collected 1971 measurements (1294 stars) of colour indice \( B-V \) and temperature (from [13] and [14]) of single stars whose spectral class span from main-sequence to giants with [Fe/H] between -0.2 to 0.2 in order to represent the solar abundance stars. Then the polynomial fittings were carried out to see how much our result deviates from either [14] or [15]. Figure 2 shows their 2σ data fitting coefficients of [14, 15], and this study as shown in equation (2).

\[
\log T_{\text{eff}} = a + b(B-V) + c(B-V)^2 + d(B-V)^3 + ... \\
\]

where \( a = 3.98384, b = -0.78156, c = 1.89140, d = -3.50793, e = 3.49615, f = -1.73609, \) and \( g = 0.33825 \) for our fitting.

For intermediate-mass binaries, the relation from equation (1) can be used to determine the \( T_{\text{sys}} \). Reddening effect for nearby objects is very small, the \((B-V)_{\text{obs}}\) outside eclipse of the system can be assumed to be the intrinsic colour \((B-V)_{0}\).

For high-mass binaries, \((B-V)_{0}\) can be determined from observed \((B-V)\) and \((U-B)\) by using equation (3) given by [16]. If KIC 10417986 is nearby, using equation (1) with our observed \( B-V = -0.1 \) is corresponding to \( T_{\text{sys}} = 8479 \) K.

\[
(B-V)_{0} = \frac{(U-B) - 0.72(B-V) - 0.05(B-V)^2}{1 - 0.05(B-V)}
\]

Figure 2. The polynomial fitting between \( \log T_{\text{eff}} \) and \( B-V \) colour for the 2σ of combined data from [13] (plus signs) and [14] (opened circles) presented in panel (a). Our fitting (solid line) shows small deviation from relations given by [14] (dotted line) and [15] (dashed line).

However, in this paper our observed B-V has a considerable high observational error and with unknown U-B, we preferably adopted method 1 to estimate \( T_{\text{sys}} = 6777 \pm 157 \) K.

5. The absolute dimension estimation

In this paper, despite without radial velocity curves, we can estimate the a and q by assuming the binary is contact with component stars are main-sequence stars.

Figure 1 suggests that light curves from Kepler and TESS of KIC 10417986 can be fitted well simultaneously in mode 5 (a contact binary). The \( T_{\text{sys}} \) of the systems with dwarf star components were concluded as the temperature of the hotter star \( (T_1) \) [12]. Thus the initial \( T_1 \sim T_{\text{sys}} = 6777 \pm 157 \) K.
The stellar radius and mass is then calculated from a polynomial fit to the temperature/radius relation for main-sequence stars given in [12].

\[
\frac{R}{R_\odot} = -3.925 \times 10^{-14} (T_{\text{sys}})_1^4 + 8.3909 \times 10^{-10} (T_{\text{sys}})_1^3 + 6.555 \times 10^{-6} (T_{\text{sys}})_1^2 + 0.02245 (T_{\text{sys}})_1 - 27.9788
\]

Using equations (4), (5) and a well-known relation \(R_2 = (r_2/r_1)R_1\) given in [17] with \(T_{\text{sys}} = 6777 \pm 157\) K, absolute dimensions \(R_1, R_2, M_1\) and \(M_2\) were determined. After acquiring the \(R_{\text{ratio}} = R_2/R_1 = 1.0 \pm 0.2\) and \(T_{\text{ratio}} = T_2/T_1\) from table 1, \(T_1\) and \(T_2\) were determined by using equation (6) - (7) given in [17].

\[
T_1 = \left(\frac{1 + R_{\text{ratio}}^2}{1 + R_{\text{ratio}}^4}\right)^{0.25}
\]

(6)

\[
T_2 = T_1T_{\text{ratio}}
\]

(7)

With new resolved \(T_1\) and \(T_2\), light curves were be fitted simultaneous again for the last time to adjust minor temperature-dependent parameters \((x_1, x_2, g_1, g_2, \text{and } A_1, A_2)\) as presented in table 1. Luminosities of each components were then determined from equation (8).

\[
L_{1,2} = R_{1,2}^4 T_{1,2}^4
\]

(8)

where \(L_{1,2}\) are luminosity in \(L_\odot\), \(R_{1,2}\) are absolute radii in \(R_\odot\), and \(T_{1,2}\) are temperature in \(T_\odot\).

Using our derived \(R_1\) and relative radii \(r_1\) and \(r_2\) presented in table 1 denoted as \(r_{1,2} = R_{1,2}/a\) we found \(a = 3.7 \pm 0.4\) \(R_\odot\) and \(q = 1.0 \pm 0.2\).

Absolute dimensions of KIC 10417986 were presented in table 2 and the Roche lobe configuration drawn by using the parameters from tables 1 and 2 was presented in figure 3.

| Table 2. Absolute dimensions of KIC 10417986 |
|-----------------------------|-----------------|
| Parameters                  | Solution        |
| \(T_1\) (K)                 | 6751 ± 900 (−F5 star*) |
| \(T_2\) (K)                 | 6804 ± 907 (−F5 star*) |
| \(R_1\) (R_\odot)           | 1.48 ± 0.05     |
| \(R_2\) (R_\odot)           | 1.4 ± 0.3       |
| \(M_1\) (M_\odot)           | 1.64 ± 0.07 (or ~1.4*) |
| \(M_2\) (M_\odot)           | 1.6 ± 0.4 (or ~1.4*) |
| \(L_1\) (L_\odot)           | 4 ± 3           |
| \(L_2\) (L_\odot)           | 4 ± 4           |
| \(a\) (R_\odot)             | 3.7 ± 0.4       |
| \(q = M_2/M_1\)             | 1.0 ± 0.2       |

Note: All presented errors are propagational errors
* Masses estimated from \(T_1\) and \(T_2\) using the MK spectral type – temperature calibration given in [18] for −F5 star with mass of ~1.4 M_\odot.
Figure 3. Roche lobe configuration of KIC 10417986 using parameters from tables 1 and 2.

Figure 4. Light curve of KIC 10417986 generated from SWASP\(^3\).

6. Conclusion and discussion
The aim of this paper is to provide methods to determine physical parameters of a given Kepler EB (without any radial velocity curves) as an example for school projects. Unpublished light curves of KIC 10417986 from Kepler and TESS online archives were analysed simultaneously by WD to derived

\(^3\) Super Wide Angle Search for Planets available online at https://wasp.cerit-sc.cz/
relative photometric parameters (as shown in table 1). On an assumption that the system is a contact binary system whose components are main-sequence stars, absolute dimensions were determined (as shown in table 2).

We found that such a very short period (0\textdegree.073731) KIC 10417986 might not play such a good example for school project due to its very low amplitude of variation in light curves (~0.0007 magnitude) that can lead someone think it is not a variable star.

However, we conclude that the system is interesting since the SWASP light curve (shown in figure 4) shows pretty obvious brightness modulation implying that it might have high mass transfer from primary to secondary star.

For our future work, in order to confirm what type of variable star this system belong to, the long-term O-C with eclipse timings cover 3-5 years is now collected. Carefully and fast (0.53 -1 min/shot) photometric observations are now scheduled. Full observed light curves should be carried out and analysed not only in mode 5 but also in other modes in WD to see differences. Other variable stars model such as a pulsating model and F-test should be tested if it can be a pulsating γ Dor or δ Sct type as suggested in [19] or not. High/medium resolution spectrum of the system should be acquired to determine spectral type of component stars, etc.

However, using the MK spectral type – temperature calibration given in [18], temperature of the primary star of 6751 ± 900 K can estimate as an ~F5 star with mass of ~1.4 M⊙. If the system turns out to be an F-type binary star with a high degree of contact, it would be suspected as an A-subtype contact binary which will ultimately become a luminous red nova at the end of the binary star evolution as proposed in [20]. To clarify this the long-term period analysis and/or O-C analysis with more eclipse timings are need to be done.

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