Orbital Period Variation of KIC 10544976: Applegate Mechanism versus Light Travel Time Effect

L. A. Almeida1,2, L. de Almeida1, A. Damineli2, C. V. Rodrigues3, M. Castro1, C. E. Ferreira Lopes3, F. Jablonski3, J-D. do Nascimento, Jr.1,4, and M. G. Pereira5
1 Departamento de Física Teórica e Experimental, Universidade Federal do Rio Grande do Norte, CP 1641, Natal, RN, 59072-970, Brazil
leonardodelalmeida@fisica.ufrn.br
2 Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Rua do Matão 1226, Cidade Universitária São Paulo, SP, 05508-090, Brasil
3 Instituto Nacional de Pesquisas Espaciais/MCTIC, Avenida dos Astronautas 1758, São José dos Campos, SP, 12227-010, Brazil
4 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
5 Universidade Estadual de Feira de Santana, Av. Transnordestina, S/N, Feira de Santana, BA 44036-900, Brazil

Received 2019 January 15; revised 2019 February 7; accepted 2019 February 20; published 2019 March 22

Abstract

In recent years, several close post-common-envelope binaries have been found to show cyclic eclipse timing variations (ETVs). This effect is usually interpreted either as the gravitational interaction among circumbinary bodies and the host binary—known as the light travel time (LTT)—effect—or as the quadrupole moment variations in one magnetic active component—known as the Applegate mechanism. In this study, we present an analysis of the ETV and the magnetic cycle of the close binary KIC 10544976. This system is composed of a white dwarf and a red dwarf in a short orbital period (0.35 days) and was monitored by ground-based telescopes between 2005 and 2017 and by the Kepler satellite between 2009 and 2013. Using the Kepler data, we derived the magnetic cycle of the red dwarf by two ways: the rate and energy of flares and the variability due to spots. Both methods resulted in a cycle of ~600 days, which is in agreement with magnetic cycles measured for single low-mass stars. The orbital period of KIC 10544976 shows only one long-term variation which can be fitted by an LTT effect with period of ~18.6 yr. Hence, one possible explanation for the ETVs is the presence of a circumbinary body with a minimal mass of ~13.4 M_Jup. In this case, the circumbinary planet must either have survived the evolution of the host binary or have been formed as a consequence of its evolution.

Key words: binaries: eclipsing – planetary systems – stars: activity – stars: flare – stars: individual (KIC 10544976) – starspots

Supporting material: machine-readable table

1. Introduction

Eclipse timing variation (ETV) is a common phenomenon in compact evolved binaries. These variations have been observed in HW Vir systems (e.g., Lee et al. 2009; Almeida et al. 2013), DA+dM eclipsing binaries (e.g., Parsons et al. 2010; Beuermann et al. 2011; Qian et al. 2012), cataclysmic variables (e.g., Dai et al. 2010), and RS CVn binaries (e.g., Liao & Qian 2010). A review on the orbital period variation of evolved compact binaries is found in Zorotovic & Schreiber (2013).

Changes in the orbital period of detached evolved compact binaries in the timescale of years to decades have been explained either by additional components interacting gravitationally with the binary causing the so-called light travel time (LTT) effect (e.g., Lee et al. 2009; Beuermann et al. 2011; Qian et al. 2012) or by magnetic activity cycles (MACs) of the main-sequence components, also known as the Applegate mechanism (e.g., Applegate 1992; Parsons et al. 2010; Bours et al. 2016). The cause of ETV is still an open issue in the literature (e.g., Bonavita et al. 2016; Bours et al. 2016; Völschow et al. 2016, 2018; Pulley et al. 2018). One possible way to disentangle the problem is to look for independent evidence of third bodies or MACs. The results on the presence of third bodies are inconclusive so far (see e.g., Marsh et al. 2014; Hardy et al. 2015, 2016; Marchioni et al. 2018). Additionally, information about the MACs in systems presenting ETV is still lacking.

KIC 10544976 (J2000: R.A. = 19°42'37"2, decl. = +47°45'48"7) is an eclipsing post-common-envelope binary consisting of a white dwarf (WD; primary) and a magnetically active M3.5-M4 dwarf star (dM; secondary) in a close orbit, \( P_{\text{orb}} \approx 0.35 \) day. The component masses are \( M_1 = 0.61 \, M_\odot \) and \( M_2 = 0.39 \, M_\odot \), totaling 1 \( M_\odot \) (Almenara et al. 2012). This object was observed by the Kepler satellite for ~3.9 yr in the short- and long-cadence modes and has been monitored since 2005 from ground-based telescopes. Searches for a third body around this system using only Kepler data were not successful (e.g., Conroy et al. 2014; Gies et al. 2015; Borkovits et al. 2016). However, this system has almost 12 yr of observational coverage and a significant number of flares in the Kepler light curve. Thus, for the first time, the same object has suitable data to measure the ETV and its MAC, allowing us to test whether these effects are correlated.

In this study, we present an orbital period analysis of KIC 10544976 and explore the two main possible scenarios that could explain the results. In Section 2, we describe the Kepler data and the data reduction of the William Herschel and Isaac Newton telescopes (INT). Section 3 presents the methodology used to obtain the mid-eclipse times, the procedures to examine the orbital period variation in the context of the LTT effect, and our approach to determine the MAC. Finally, we discuss the results in Section 4.
2. Observations and Data Reduction

2.1. Kepler Satellite

The KIC 10544976 data were retrieved from the Kepler data search webpage. We use the Presearch Data Conditioning (PDC) and the full frame images (FFIs). The PDC extracts the flux via aperture photometry and corrects the systematic effects, e.g., outliers and discontinuities within the quarters (e.g., Jenkins et al. 2010). The KIC 10544976 light curve is composed by short and long cadences. We use both cadences, which have integration time of ~1 and ~30 minutes covering ~3.9 yr from 2009 to 2013. Figure 1 shows the normalized short-cadence light curve (as described in Section 3.2.3).

The FFIs are images of the Kepler’s entire field of view. There are 53 FFIs, of which 8 of them were collected in the 34 hr period during the commissioning of the spacecraft in 2009, and the other images were obtained approximately one per month throughout the primary mission. The FFIs have the same integration time and calibration of the long-cadence data.

2.2. Isaac Newton Group of Telescopes

Raw photometric data of KIC 10544976 and calibration (flat-field and bias) images were retrieved from the Isaac Newton Group public archive. The photometric observations were performed with the Auxiliary-port CAMera attached to the 4.2 m William Herschel Telescope (WHT) and with Wide Field Camera coupled to the 2.54 m INT at Roque de los Muchachos Observatory. The observations were done on 2008 August 28 and 2014 July 21 (WHT), and on 2017 April 5 (INT). These data comprise 344 images (\(t_{\text{exp}} = 10\) s) in the \(V\) band and 1209 images (\(t_{\text{exp}} = 5\) s) plus 136 images (\(t_{\text{exp}} = 25\) s) unfiltered.

The WHT and INT data were reduced using the standard IRAF tasks, which subtract a master median bias image from each program image, divide the result by a normalized flat field, and perform differential photometry. As the KIC 10544976 field is not crowded, aperture photometry was used to extract its flux relative to a constant target (2MASS 19423960 +4744583).

3. Analysis and Results

3.1. Eclipse Fitting

The mid-eclipse times of KIC 10544976 were obtained performing a model fit to each observed eclipse using the Wilson-Devinney code (WDC; Wilson & Devinney 1971). The range of the geometrical and physical parameters, e.g., inclination, radii, and temperatures obtained by Almenara et al. (2012), were adopted as search intervals in the fitting procedure.

We use the same approach described in Almeida et al. (2013) to derive the mid-eclipse times and their uncertainties. In short, a Markov chain Monte Carlo (MCMC) procedure was performed to sample the mid-eclipse time and to examine the marginal posterior distribution of the probability of the parameters. The median of the distribution provides the mid-eclipse time and the area corresponding to the 1σ percentile provides the uncertainty. Our 2745 new mid-eclipse times from the Kepler, WHT, and INT data, and previous values obtained by Almenara et al. (2012) are presented in Table 1. We
reanalyzed the data collected on 2008 August 28 presented in Almenara et al. (2012). Our results are in agreement.

3.2. Orbital Period Variation

To analyze the ETV of KIC 10544976, we initially examined if its orbital period could be represented by a linear ephemeris as

\[ T_{\text{min}}(\text{TDB}) = T_0 + E \times P_{\text{bin}}, \]

where \( T_{\text{min}} \) are the mid-eclipse times, \( T_0 \) is an initial epoch, \( E \) is the cycle count from \( T_0 \), and \( P_{\text{bin}} \) is the orbital period. The residuals of the mid-eclipse times with respect to a linear ephemeris, also known as the observed minus calculated (\( O - C \)) diagram, show an apparent cyclic variation (see the top of Figure 2). In the following sections, we verify if the ETV can be explained by the Applegate mechanism or by the LTT effect.

3.2.1. Light Travel Time Effect

The LTT effect in the received times of a periodic source is generated by variations in the distance between this source and the observer. In the case of an eclipsing binary, the eclipse times are modulated as a result of the gravitational interaction of the binary with other bodies (Irwin 1952). Adding this effect to Equation (1), we obtain

\[ T_{\text{min}} = T_0 + E \times P_{\text{bin}} + \sum_j \tau_j, \]

where

\[ \tau_j = \frac{c}{a_{\text{bin},j}} \sin i_j \left[ \frac{1 - e_j^2}{1 + e_j \cos f_j} \sin(f_j + \omega_j) \right] \]

is the LTT effect of the \( j \)th body, \( c \) is the speed of light, \( a_{\text{bin},j} \) is the semimajor axis, \( e_j \) is the eccentricity, \( i_j \) is the inclination, \( f_j \) is the true anomaly, and \( \omega_j \) is the argument of periastron.

Using Equation (2) with only one LTT effect to fit the mid-eclipse times, the resulting \( \chi^2_{\text{red}} \) is 1.5. In the fitting procedure, we use the PIKAIA algorithm (Charbonneau 1995) to look for the global solution, followed by a MCMC to sample the parameters of Equation (2) around this solution. Figure 2 shows graphically the results and Table 2 shows the fitted and derived parameters.

3.2.2. Applegate Mechanism

The Applegate mechanism (Applegate 1992) consists of the coupling between the binary orbit and changes in the shape of a magnetically active component. These changes are generated by variations in the quadrupole moment, which are directly related to the MAC and should lead to cyclic variations of the binary orbital period.

Brinkworth et al. (2006) expanded the Applegate original expressions to include a stellar, thick outer shell. They showed that the ETV of NN Ser cannot be explained by the Applegate mechanism based on energetic grounds. Recently, Völschow et al. (2016) extended the formulation developed by Brinkworth et al. (2006) including quadrupole moment changes in two finite regions, the core and the external shell. They applied this model for 16 compact binaries and concluded that the Applegate mechanism can explain the ETV for 4 systems.

In the Applegate mechanism scenario, the observed ETV should have the same period as the MAC. In the following sections, we present the procedure to derive the MAC of KIC 10544976 via the flare occurrence rate and modulations by stellar spots.
3.2.3. Flare Analysis

The *Kepler* light curve of KIC 10544976 presents many flares. The flares are observed in any phase of the orbital cycle, including in the primary eclipses, which points to an origin in the secondary star, probably due to its magnetic activity (see Figure 1). The occurrence rate and energy of the flares have been used to derive the stellar magnetic cycle. The periodicity of these quantities is well known to be in good agreement with the MAC derived via photometric modulations generated by stellar spots for the Sun, solar-type, and low-mass stars (e.g., Basri et al. 2010; Savanov 2012; Mathur et al. 2014; Montet et al. 2017; He et al. 2018).

To calculate the frequency and energy of the KIC 10544976 flares in the short-cadence *Kepler* light curve, we use the following steps.

(i) The jumps in the PDC light curves among the quarters were corrected and then, the whole data normalized.

(ii) A phase diagram was built using the orbital period and initial epoch shown in Table 2 in order to subtract the reflection effect by fitting a sinusoidal function and to shift the inner part of the WD eclipses to the external level.

(iii) An automatic task was developed to find the flares. Our task searches for outliers (or peaks), whose we consider as flare candidates when three consecutive points follow the criterion

\[
\frac{(y_i - \bar{y}_{\text{ML}})}{\sigma_{\text{ML}}} \geq 3, \tag{4}
\]

where \(y_{\text{ML}}\) and \(\sigma_{\text{ML}}\) are the average and the standard deviation computed in the box of fixed \(L = 0.035\) d size. The false flare candidates, those that do not follow the flare standard behavior, i.e., a rapid rise and a slow exponential decrease, were removed by visual inspection and 211 flare candidates were confirmed as bona fide flares. The positions of all the flares in the light curve are shown in Figure 1 with the gray vertical lines. To search for periodicity in the flare occurrence rate, we count the flares in boxes with the same timescale as the files available by *Kepler*, which have \(\sim 30\) days. The number of flares, their Lomb–Scargle (LS) periodogram, and the phase diagram for the frequency of maximum power (equivalent to \(P = 600 \pm 134\) days) are shown in the top panels of Figure 3 (yellow marks). The frequency uncertainty was derived by fitting a Gaussian function in the maximum peak of the periodogram.

(iv) We also use a flare index \(P_{\text{flare}}\) proposed by He et al. (2018). This index is equivalent to the flare energy rate. The results for \(P_{\text{flare}}\) taking the same size boxes as used for the flare counting is shown in the top left panel of Figure 3 (blue marks). To search for periodicity, we removed a point that has more than 3\(\sigma\) above the average of the whole sample. This point (shown as an empty square in the \(P_{\text{flare}}\) data in Figure 3) is due to a long-lasting flare and has a strong influence in the search for periodicity based in the LS method. The LS periodogram and phase diagram are displayed in the top right and middle panels of Figure 3. The maximum power frequency is equal to \(550 \pm 101\) days.
3.2.4. Spot Modulation Analysis

As the secondary star shows a significant number of flares a contribution of the spots is expected in the Kepler light curve. This effect can also provide information about magnetic cycles (e.g., Oláh et al. 2009; Savanov 2012; Vida et al. 2013, 2014; Ferreira Lopes et al. 2015; Montet et al. 2017). This question was addressed analyzing the PDC long-cadence light curve and the FFIs in the following ways:

(i) The PDC long-cadence light curve was normalized following the same procedure used for the flare analysis, see Section 3.2.3.

(ii) We applied multiplicative factors among the quarters to account for the different aperture masks adopted by the Kepler pipeline. These factors were calculated to produce equal eclipse depths and reflection effect amplitudes among the quarters. We are confident that this procedure preserves the original long-term behavior of the KIC 10544976 light curve because the signal of $\sim 372.5$ days due to the Kepler heliocentric orbital period was conserved (see, e.g., Van Eylen et al. 2013).

(iii) The flare and eclipse regions were cut and a sigma clipping ($3\sigma$) was performed to remove other outliers. The 372.5-day signal was also subtracted using a sinusoidal fit.

(iv) The stellar activity proxy $R_{\text{var}}$, defined as the difference between the 5% and 95% percentile intensities (Basri et al. 2010), was computed in time boxes as those used for the flares. The results for $R_{\text{var}}$ are present in the bottom panels of Figure 3 (green marks). The maximum power frequency in the LS periodogram show two peaks, 585 $\pm$ 92 and 694 $\pm$ 130 days. As an example of how the spots increase the dispersion in the light curve, Figure 4 shows two normalized and phased light curves of 30 day ranges, which have high (top panel) and low (bottom panel) incidence of spots.

(v) We applied the method developed by Montet et al. (2017) to measure the long-term variability of KIC 10544976 using the FFIs. Their Full Frame Fotometry package\(^{11}\) was used to obtain the relative flux of our target with respect to nearby reference stars on the detector. To correct the variability due to the binary variation, the first eight images, obtained during 34 hr, were modeled using the WDC, and this information was applied to all other 32 available FFIs for KIC 10544976. The result of this procedure, its LS periodogram, and the phase diagram for the period of 544 $\pm$ 88 days, which corresponds to the highest power frequency, are presented in the bottom panels of Figure 3 (magenta marks). One point was removed in the search for periodicity using the same criterion adopted for the $P_{\text{flare}}$ (see the empty square in the bottom panel of Figure 3).

4. Discussion and Conclusions

In this study, we present an orbital period variation analysis of the post-common-envelope binary KIC 10544976. We combined 2745 new mid-eclipse times from Kepler, WHT, and INT data with measurements available in the literature and performed a linear ephemeris fitting. One cycle with a semi-

\(^{11}\) https://github.com/benmontet/f3

\(^{12}\) http://theory-star-formation-group.cl/applegate/index.php
counting and energy rate \( (P_{\text{flare}}) \) as well as modulations and long-term variations in the light curve generated by stellar spots. The LS periodograms of the flare count and \( P_{\text{flare}} \) show maximum peaks at 600 ± 134 days and 550 ± 101 days, which agree within the uncertainties. Whereas for the spot modulations, represented by the stellar activity proxy \( R_{\text{spot}} \), the maximum frequency in the LS periodogram has two peaks (585 ± 92 and 694 ± 130 days), the long-term variability, expressed by the relative flux, shows only one with a period of 544 ± 88 days. Hence, all periods associated with flares and stellar spots agree with each other within the uncertainties, see Figure 3. Therefore, we conclude that the MAC of the KIC 10544976 secondary star has a period around 600 days.

To check if the measured magnetic cycle for the KIC 10544976 secondary star is in agreement with the other low-mass single stars, we use the MAC versus rotation period diagram. Under the reasonable assumption of synchronization between the secondary component and the orbital period of the system, its rotation period was considered to be 0.35 days. The relation between the magnetic cycle and rotation period for the secondary star agrees with the other values measured for low-mass dM single stars (see Figure 5). This result strengthens the MAC found in this study.

Furthermore, it is possible to verify if the secondary star magnetic cycle has some influence at the KIC 10544976 orbital period by checking the residuals (middle panel of Figure 2) of the \((O - C)\) diagram. The LS periodogram (bottom panel of Figure 2) does not show any significant period around 600 days. Additionally, we can also exclude any variation with a semi-amplitude larger than ~2.6 s in the residuals.

Considering that the LTT effect is the real cause for the KIC 10544976 orbital period variation, there are two principal scenarios for planetary formation to take place: the first generation of planets formed from a circumbinary protoplanetary disk and the second generation of planets originated from the mass ejected by the common envelope (Perets 2011). Zorotovic & Schreiber (2013) studied the origin of the ETVs in post-common-envelope binaries and found that the second-generation scenario is more probable than the first-generation one. Due to its magnitude \( (R = 18.7) \) and sky position, the new generation of giant telescopes, such as the Thirty Meter Telescope\(^{13}\) equipped with the chronograph, Planetary System Instrument available at the second generation of instruments, will be crucial to directly confirm the third body around KIC 10544976.

We thank the anonymous reviewer for the careful reading of our manuscript as well as for the useful suggestions to improve it. This study was partially supported by CAPES, FAPESP (L.A.A. and A.D.: 2011/51680-6, L.A.A.: 2012/09716-6, 2013/18245-0, and C.V.R.: 2013/26258-4), and CNPq (CVR: 306701/2015-4). This paper includes data collected by the Kepler mission. Funding for the Kepler mission is provided by the NASA Science Mission directorate. This paper makes use of data obtained from the Isaac Newton Group of Telescopes Archive which is maintained as part of the CASU Astronomical Data Centre at the Institute of Astronomy, Cambridge.

**ORCID iDs**

L. A. Almeida \( \text{https://orcid.org/0000-0002-3817-6402} \)

L. de Almeida \( \text{https://orcid.org/0000-0001-8179-1147} \)

C. V. Rodrigues \( \text{https://orcid.org/0000-0002-9459-043X} \)

J.-D. do Nascimento, Jr. \( \text{https://orcid.org/0000-0001-7804-2145} \)

**References**

Almeida, L. A., Jablonski, F., & Rodrigues, C. V. 2013, ApJ, 766, 11

Almenara, J. M., Alonso, R., Rabus, M., et al. 2012, MNRAS, 420, 3017

Applegate, J. H. 1992, ApJ, 385, 621

Basri, G., Walkowicz, L. M., Batalha, N., et al. 2010, ApJL, 713, L155

Beuermann, K., Buhlmann, J.,Diese, J., et al. 2011, A&A, 526, A53

Bonavita, M., Desidera, S., Thalmann, C., et al. 2016, A&A, 593, A38

Borkovits, T., Hajdu, T., Sztkovics, J., et al. 2016, MNRAS, 455, 4136

Bours, M. C. P., Marsh, T. R., Parsons, S. G., et al. 2016, MNRAS, 460, 3873

Brinkworth, C. S., Marsh, T. R., Dhillion, V. S., et al. 2006, MNRAS, 365, 287

Charbonneau, P. 1995, ApJS, 101, 309

Conroy, K. E., Pišta, A., Stassun, K. G., et al. 2014, AJ, 147, 45

Dai, Z.-B., Qian, S.-B., Fernández Lajús, E., & Baume, G. L. 2010, MNRAS, 409, 1195

Fernanda Lopes, C. E., Leão, I. C., de Freitas, D. B., et al. 2015, A&A, 583, A134

Gies, D. R., Matson, R. A., Guo, Z., et al. 2015, AJ, 150, 178

Hardy, A., Schreiber, M. R., Parsons, S. G., et al. 2015, ApJL, 800, L24

Hardy, A., Schreiber, M. R., Parsons, S. G., et al. 2016, MNRAS, 459, 4518

He, H., Wang, H., Zhang, M., et al. 2018, ApJS, 236, 7

Irwin, J. B. 1952, ApJ, 116, 211

Jenkins, J. M., Caldwell, D. A., Chandrasekharan, H., et al. 2010, ApJL, 713, L87

Lee, J. W., Kim, S.-I., Kim, C.-H., et al. 2009, AJ, 137, 3181

Liao, W.-P., & Qian, S.-B. 2010, MNRAS, 405, 1930

Marchioni, L., Guinan, E. F., Engle, S. G., et al. 2018, RNAAS, 2, 179

Marsh, T. R., Parsons, S. G., Bours, M. C. P., et al. 2014, MNRAS, 437, 475

Mathur, S., García, R. A., Ballot, J., et al. 2014, A&A, 562, A124

Montet, B. T., Tovar, G., & Foreman-Mackey, D. 2017, ApJ, 851, 116

\(^{13}\) https://www.tmt.org/
The Astronomical Journal, 157:150 (7pp), 2019 April

Oláh, K., Kolláth, Z., Granzer, T., et al. 2009, A&A, 501, 703
Parsons, S. G., Marsh, T. R., Copperwheat, C. M., et al. 2010, MNRAS, 407, 2362
Perets, H. B. 2011, in AIP Conf. Ser. 1331, Planetary Systems Beyond the Main Sequence, ed. S. Schuh, H. Drechsel, & U. Heber (Melville, NY: AIP), 56
Pulley, D., Faillace, G., Smith, D., Watkins, A., & von Harrach, S. 2018, A&A, 611, A48
Qian, S.-B., Zhu, L.-Y., Dai, Z.-B., et al. 2012, ApJL, 745, L23
Savanov, I. S. 2012, ARep, 56, 716
Van Eylen, V., Lindholm Nielsen, M., Hinrup, B., Tingley, B., & Kjeldsen, H. 2013, ApJL, 774, L19
Vida, K., Kriskovics, L., & Oláh, K. 2013, AN, 334, 972
Vida, K., Oláh, K., & Szabó, R. 2014, MNRAS, 441, 2744
Völschow, M., Schleicher, D. R. G., Banerjee, R., & Schmitt, J. H. M. M. 2018, A&A, 620, A42
Völschow, M., Schleicher, D. R. G., Perdelwitz, V., et al. 2016, A&A, 587, A34
Wilson, R. E., & Devinney, E. J. 1971, ApJ, 166, 605
Zorotovic, M., & Schreiber, M. R. 2013, A&A, 549, A95