O' Connell Effect and Period Variations in the Solar-like Contact Binary EF Boo (Postprint)

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Abstract

Using ground-based telescopes, multi-color photometric observations of the contact binary EF Boo were obtained in 2020, 2023, and 2024. Combining these with light curves from seven sectors of TESS data, variations of the O' Connell effect in continuous time and changes in light curve morphology over several years were identified. Three sets of typical light curves were analyzed to determine photometric solutions via the Wilson–Devinney program. Considering the spectroscopic mass ratio of q = 0.53, these photometric solutions suggest that EF Boo is a W-type W UMa contact binary with an average filling factor of f = 22.26%, a small temperature difference, and a cool spot on the primary component. If the variations of the O' Connell effect are attributable to the magnetic activity of this cool spot, the longitudinal location varied from over a time interval of 1434 days. Based on all CCD minimum times from ground-based telescopes and TESS data, the O − C curve was also analyzed. For the first time, a cyclic oscillation (A3 = 0.00575 days, T3 = 27.8 yr) superimposed on a secular increase (dP/dt = 6.74 × 10−8 day yr−1) was discovered. The secular increase is possibly a result of mass transfer from the less massive star to the more massive one. The cyclic oscillations may be explained by the light-travel time effect due to a third body or by magnetic activities. From the short-cadence observations from TESS, we also calculated the O' Connell effect value and O − C value for each cycle and found no correlation between the O' Connell effect and O − C over nearly 30 days across different sectors.

Full Text

Preamble

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O’ Connell Effect and Period Variations on Solar-like Contact Binary EF Boo

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Abstract

Using ground-based telescopes, we obtained multi-color photometric observations of the contact binary EF Boo in 2020, 2023, and 2024. Combining these with seven sectors of light curves from TESS data, we identified variations of the O’ Connell effect over continuous time and changes in light curve shapes spanning several years. Three sets of typical light curves were analyzed to determine photometric solutions via the Wilson–Devinney program.

Considering the spectroscopic mass ratio of q = 0.53, these photometric solutions suggest that EF Boo is a W-type W UMa contact binary with an average filling factor of f = 22.26%, a small temperature difference, and a cool spot on the primary component. If the variations of the O’ Connell effect are due to the magnetic activity of this cool spot, its longitudinal location varied from 50°.4 to 302°.7 over a time interval of 1434 days. Based on all CCD minimum times from ground-based telescopes and TESS data, we also analyzed the O − C curve. For the first time, we discovered a cyclic oscillation (A_3 = 0.00575 days, T_3 = 27.8 yr) superimposed on a secular increase ($dP/dt = 6.74 \times 10^{-8}$ day yr^{-1}). The secular increase is possibly a result of mass transfer from the less massive star to the more massive one. The cyclic oscillations may be explained by the light-travel time effect via a third body or by magnetic activities. From the short-cadence observations from TESS, we also calculated the value of the O’ Connell effect and O − C value for each cycle and found no correlation between the O’ Connell effect and O − C over nearly 30 days across different sectors.

Key words: (stars:) binaries (including multiple): close -(stars:) binaries: eclipsing -stars: solar-type -stars: individual (EF Boo)

1. Introduction

During the orbital period of contact binaries, two distinct eclipses and two intervening maxima are observed. As a result, the maximum brightness or flux should theoretically be the same. However, variations in the brightness maxima of these photometric light curves (LC) have been noted by Roberts

(1906), Mergentaler (1950), and O’ Connell (1951), and are known as the O’ Connell effect, which was first investigated in the contact binary RT Lac by Milone (1968). A search for the O’ Connell effect in 5374 eclipsing binary stars from the ASAS database (Papageorgiou et al. 2014) pointed out that the range of magnitude difference between the two maxima, |MaxI–MaxII|, is 0.025–0.1 mag. Knote et al. (2022) analyzed Kepler eclipsing binaries and characterized a set of 212 systems with a maximum flux difference of at least 1%, suggesting that interaction between closely orbiting components ultimately leads to the O’ Connell effect. Among 107 contact binaries from the Hipparcos satellite, these phenomena in late-type contact binaries are more common compared with other types, especially noting that the magnitude difference of G-type ones is less than 0.04 mag (Pribulla et al. 2011; Hwang & Zakamska 2020), such as EQ Tau, FG Hya, UV Lyn, and KIC systems.

The O’ Connell effect and its variations in late-type binaries are often attributed to magnetic activities of star spots (Mullan 1975; Wilsey & Beaky 2009; Heinze 2023; Liu & Yang 2003). For low-mass, cool-temperature late-type stars, these small amplitude differences in maximum brightness are considered direct evidence of spot activity on the surface of at least one component. Recently, Kouzuma (2019) investigated 102 contact binaries with cool spots and concluded that magnetic activity in W-type contact binaries is likely caused by stellar dynamos. Spot locations on five low-mass eclipsing binaries changed over several years, notably for NSVS 02502726, where a starspot ranging from 180° to 360° indicated a magnetic activity cycle of 5.9 yr (Zhang et al. 2014). Shi et al. (2021) observed that the O’ Connell effect, due to spot properties, varies with a cycle length of approximately 2000 days from Kepler and TESS light curves for the Algol-type binary system KIC.

Additionally, orbital period variations exhibit various behaviors, including secular increases, decreases, and periodic oscillations. Generally, these oscillations are attributed to a third body around the binary system, though Applegate (1992) suggested that non-strict variations may result from magnetic activities. Yilmaz et al. (2023) studied star spots in the contact binary PP Lac, indicating that eclipse timing variations (ETVs) are attributed to the magnetic activity cycle combined with the presence of a third body. Using 27 sets of new photometric observations from the last 5 yr, Pi et al. (2019) found that the cyclic oscillation of the O’ Connell effect with 5.15 yr is shorter than the 14.58 yr oscillation observed in the $O - C$ curve of the orbital period.

We hope to discover solar-like contact binaries with continuous variation in the O’ Connell effect, period variations, and spots to further understand the evolution and magnetic activities of binary stars. EF Boo is a W-subtype contact binary discovered by Hoeg et al. (1997). Basic parameters, including G5 spectral type and EB-type light curves, were obtained by Perryman et al. (1997). From 1999 to 2017, seven studies presented results summarized in Table 1. This target exhibits an obvious O’ Connell effect and variations in light curves, with varying solutions over time. In this work, we monitored EF Boo in 2020, 2023, and 2024 using ground-based telescopes and obtained TESS observations. These light curves were used for analyzing continuous variations in the O' Connell effect, orbital period variations, and re-evaluating the photometric solutions. Based on these properties, we discuss the ternary nature, magnetic activity, and evolution of the system.

Some Investigations on the Contact Binary EF Boo

Parameters	References
$M_2/M_1 = 0.57$, $\Delta T = 100$ K, f = 25%	Samec et al. (1999)
W-Type, F5+lateG, period = 0.4205 days	Gothard et al. (2000)
$M_2/M_1 = 0.51$, $\Delta T = 112$ K, f = 28%	Rucinski et al. (2001)
$M_2/M_1 = 0.45$, f = 20%	Ozdemir et al. (2004)
$M_2/M_1 = 0.53$, $\Delta T = 25$ K, f = 18%	Selam (2004)
continuous period increase	Gazeas et al. (2005)
O' Connell effect	Yu et al. (2017)

Information for Observations of the Contact Binary EF Boo

Years	Exposure times	Effective field	Camera	Telescope
Mar 16, Apr 28, Jun 13	B 40 s, V 30 s, Rc 20 s, Ic 10s	13 .5 × 13 .5	2048 × 2048 DZ936N	60 cm
Jun 1, Jun 30	B 10 s, V 5 s, RcIc 3s	16 .5 × 16 .5	1024 × 1024 PI1024 BFT	85 cm
May 20, Jun 14, Jun 16	B 5 s, VRcIc 3 s	16 .5 × 16 .5	1024 × 1024 PI1024 BFT	85 cm

Coordinates of the Contact Binary EF Boo (V), the Comparison (C) and the Check Stars (Ch)

Stars	α_{2000}	δ_{2000}
EF Boo(V)	14 32 30 .57	+46°46 57 .3
HD 127807(C)	14 31 46 .31	+46°52 40 .8
HD 234152(Ch)	14 33 32 .05	+46°45 14 .9

2. Observations

2.1. Ground-based Telescope

The multi-color photometric observations listed in Table 2 were carried out with 60 cm and 85 cm telescopes (Zhou et al. 2009) in different years at XingLong Station of the National Astronomical Observatories of the Chinese Academy of Sciences. On 2020 March 16, due to a malfunction in the filter system, we only obtained the V-band light curve.

All observed images were reduced using the C-MuniPack program (http://c-munipack.sourceforge.net/), including bias correction, flat-fielding, aperture photometry, and differential photometry operations. The variable star (V), the comparison star (C), and the check star (CH) are listed in Table 3. The observational errors in the BVRcIc bands are less than 0.004 mag. These observations, including their magnitudes and Barycentric Julian Dates (BJD), are depicted in Figure 1. Due to constraints imposed by weather conditions and the eclipsing period, complete curves were not obtained for the entire night; however, the EW-type light curves are clearly discernible.

Using the linear ephemeris equation (Yu et al. 2017), we acquired the light curves (LCs) along with the orbital phase from three sets of observations in 2020 and 2024. On the left side of Figure 2, these LCs were collected with the 60 cm telescope in 2020, while the right side shows curves obtained with the 85 cm telescope in 2024. The heights between the maximum light of individual LCs are nearly the same, indicating that there is no O' Connell effect. These curves are helpful for obtaining reliable photometric solutions, and several CCD times of minimum light were determined and listed in Table 4. While any small amplitude variations may have been neglected, we focus on the fact that the heights of maximum light in 2020 are obviously different from those in 2024, indicating that the components are possibly active.

2.2. TESS Light Curves

The Transiting Exoplanet Survey Satellite (TESS) provides high-precision continuous light curves with a 2-minute short cadence, available from the MAST website (https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html). From 2019 September to 2024 April, seven sectors of light curves were released, with flux errors of less than 35 e^{-}/s (~0.0008 mag). These observations can be used to analyze small intrinsic variations of the O' Connell effect, as shown in Figure 3. In Sector 22, the flux of the primary maximum equals the secondary one, but they show a noticeable difference in Sector 76. The continuous variations in the O' Connell effect were caught for the first time.

To investigate the intrinsic light variability throughout each complete period, we computed the flux differences around two maxima and minima. Specifically, the fluxes at phases 0.0, 0.25, 0.5, and 0.75 are labeled as Min.I, Max.I, Min.II, and Max.II, respectively. In Figure 4, these fluxes are plotted over time in each sector. The red dots denote Min.I and Max.I, while the black dots represent Min.II and Max.II.

For each period, we also calculated the differences between the maxima and minima. On the left side of Figure 4, the red lines indicate that the flux at Max.I exceeds Max.II (positive O' Connell effect), while the green lines signify the opposite (negative O' Connell effect). Similarly, on the right side, these lines represent the minima.

In the last sector plotted from Sector 77 of TESS data, no O' Connell effect is found in the LCs (Ozdemir et al. 2004; Gazeas et al. 2005). Despite the potential influence of systematic telescope errors on these few data points, they hold significant value for other sector light curves. In essence, these differences between two maxima or minima are meaningful.

In the 1st (Sector 16), 4th (Sector 49), 5th (Sector 50), and 6th (Sector 76) rows of Figure 4, we see that the flux at the primary maximum and minimum is less than that at the secondary ones. The 2nd (Sector 22) and 3rd (Sector 23) rows exhibit significant variations, particularly in Sector 22, where the effect transitions from negative to positive, with Max.I being brighter than Max.II. These phenomena may result from magnetic activities on the components, such as star spots not only migrating across the stellar surface but also evolving rapidly. These dynamic changes suggest complex underlying processes driving the movement and transformation of these regions, potentially offering deeper insights into stellar magnetic activity and behavior.

3. Variations of Orbital Period

Using light curves from ground-based telescopes and TESS, we have directly determined numerous eclipsing times and compiled additional CCD timings from various literature sources and the O-C gateway (http://var2.astro.cz/ocgate/index.php). However, since visual timings with larger errors show considerable scatter (Yu et al. 2017), we have opted to use photoelectric and CCD data to analyze variations in the orbital period. The Heliocentric Julian Dates (HJD) were converted into Barycentric Julian Dates (BJD; Eastman et al. 2010). A comprehensive list of all 105 ground-based telescope timings is provided in Table 4, though the long-term variation should be analyzed. It is noted that due to the brief duration of the TESS $O - C$ values, 346 data points in our analysis are not provided individually.

Based on the ephemeris equation (1), we calculated the $(O - C)_1$ values listed in Table 4, which were plotted in the upper panel of Figure 5. The solid circles represent the primary minimum times, the hollow circles represent the secondary ones, and the blue points refer to times derived from TESS data. Considering the continuous period increase reported by Yu et al. (2017), we also applied a parabolic fit to the $(O - C)_1$ values, indicated by the dashed lines. Additionally, after subtracting the long-term increase, a cyclic term was identified and shown in the middle panel. The final residuals are listed in Table 4 and plotted at the bottom of Figure 5, supporting the reliability of the combination of cyclic and parabolic ephemeris.

The fitting results yield the following equation using methods from Irwin (1952) and Sterken (2005):

$$\text{Min.I BJD} = 2451282.83637 + 0.42050792 \times \text{E} + 0.00009 \sin(0.014914 \times \text{E})$$

where A_3 is the amplitude of sinusoidal variation, T_3 is the period of the cycle, $\omega = 2\pi/P$ is the angle per unit epoch, and f is the phase. The second-order term suggests a long-term period increase at a rate of $dP/dt = 6.74 \times 10^{-8}$ day yr^{-1}, while the sinusoidal oscillation indicates an amplitude of 0.00575 days and a period of 27.8 yr.

The cyclic oscillations in the O − C diagram are commonly attributed to the light-travel time effect caused by the presence of a third body. However, Applegate (1992) suggested that these oscillations may result from magnetic activities. The hypothesis is that the O' Connell effect is a significant indicator of magnetic spot activity. Due to the discontinuous nature of ground-based observations taken at different times, we cannot capture the continuous variation of the O' Connell effect and explore its relationship with O − C thoroughly. Koju & Beaky (2015) found no correlation between the O' Connell effect and orbital period change for SW Lac, CN And, and V502 Oph. The period of the O' Connell effect was found to be shorter than the cyclic oscillations in the O − C diagram for eclipsing binary DV Psc (Pi et al. 2019). From the short-cadence observations from TESS, we simply calculated the value of the O' Connell effect and O − C for each cycle. In Figure 6, on the left, the flux difference between two maxima is plotted as black dots, showing noticeable variations of the O' Connell effect without apparent regularity. On the right, the O − C values of Min.I times are represented as red dots, and Min.II times as black dots. We also found no correlation between the O' Connell effect and O − C over nearly 30 days across different sectors.

4. Photometric Solutions by the W-D Code

From Table 1, it is evident that the parameters derived from these investigations are different, such as the mass ratio, temperature difference, and degree of fill-out. However, Gazeas et al. (2005) determined the spectroscopic mass ratio of $M_2/M_1 = 0.53$, where M_1 represents the primary star (the star eclipsed at primary light minimum).

In our study, photometric solutions were obtained using the W-D program (Wilson & Devinney 1971; Wilson 1990; Wilson & Van Hamme 2014; Wilson 2020). According to the TESS Input Catalog (v8.0) (Stassun et al. 2019), the new effective temperature of the more massive component was fixed at T = 6320 K, corresponding to an F-type star. Considering the convective atmospheres of the components, the same values of the gravity-darkening coefficients ($g_1 = g_2 = 0.32$; Lucy 1967) and the bolometric albedo ($A_1 = A_2 = 0.5$; Ruciński 1969) were adopted in the model.

Since symmetric complete light curves were only available in 2020 using the 60 cm telescope, we used these data to find converged solutions. The spectroscopic mass ratio of 0.53 was adopted for the W-D code. The maximum flux difference between maxima in positive O' Connell effect light curves is 423 e^{-}/s, while in negative curves, the maximum difference is -825 e^{-}/s. We analyzed them separately, as displayed in Figure 9, to derive converted solutions and configurations with dark spots. Remarkably, we discovered the migration of the cool spot from 50°.4 to 302°.7 on the primary component.

The derived results are detailed in Table 5. Notably, the identified errors are exclusively a product of the fitting process within the WD code. These parameters indicate that EF Boo is a W-type shallow-contact binary; the effective temperatures of the two components are nearly identical with an average fill-out of 22.26%.

5. Discussion and Conclusion

We carried out multi-color BVRcIc-band observations using ground-based telescopes several times in 2020, 2023, and 2024. In these light curves, although the O' Connell effect was sometimes absent, significant variations were noted across different years. Additionally, analysis of seven sectors of light curves from TESS data revealed the presence of a variable O' Connell effect. As presented by Samec et al. (1999) and Gothard et al. (2000), these phenomena suggest that the contact binary EF Boo may be active.

The complete light curves obtained in 2020, along with two TESS light curves exhibiting O' Connell effects, were used to analyze the photometric solutions of this contact binary. These solutions suggest that the system is a typical W-type contact binary with a degree of contact of f = 22.26%, a mass ratio of $q = M_2/M_1 = 0.53$, and a small temperature difference between the two components, indicating that both components share a common convective envelope. These results confirm the parameters calculated by Selam (2004) and Gazeas et al. (2005).

From the positive O' Connell effect in the light curve, we derived the presence of one cool spot, adjusting its location to fit the negative curve accurately. Thus, we infer that this spot is migrating, causing the O' Connell effect and light curve variations. In the light curves showing the two O' Connell effects, the flux differences are at maximum and minimum values, respectively, with a time interval of 1434 days. If the variation in the O' Connell effect is due to this cool spot, its longitudinal location varied from 50°.4 to 302°.7 over the same time interval.

The $O - C$ diagram shown in Figure 5 reveals a long-term increase and cyclic oscillation. The orbital period of EF Boo is increasing at a rate of $dP/dt = 6.74 \times 10^{-8}$ day yr^{-1}. The absolute parameters of this system were estimated as $M_1 = 1.547$ M , $R_1 = 1.431$ R and $M_2 = 0.792$ M , $R_2 = 1.064$ R (Gazeas et al. 2005). Using the following equation (Singh & Chaubey 1986), the mass transfer rate was determined to be $dM_2/dt = -8.67 \times 10^{-8}$ M yr^{-1}. Thus, the long-term increase of the orbital period is possibly due to mass transfer from the less massive component to the more massive one. The cyclic oscillations (A_3 = 0.00575 days, T_3 = 27.8 yr) are typically explained by the light-travel time effect via a third body (Liao & Qian 2010; Qian et al. 2012, 2015). Using the same method as Zhu et al. (2013a, 2013b), if the orbital inclination i is 90°, the mass of the third body should be $m_3 = 0.201$ M with a maximal orbital radius of $a_3 = 11.55$ au.

Considering the cool spot on the surface of the primary component, Applegate (1992) suggested that the oscillation could be due to magnetic activities. The quadrupole moment variations of the component stars were calculated using these equations (Applegate 1992; Lanza & Rodonò 2002):

$\Delta P/P = -9\Delta Q/(M\ a^2)$

For the active components, we determined $\Delta Q_1 = 5.93 \times 10^{49}$ g cm^{-2} and $\Delta Q_2 = 3.03 \times 10^{49}$ g cm^{-2}, similar to some active contact binaries such as J082700 (Li et al. 2021), V694 Peg (Xu & Zhu 2014), and OO Leo (Meng et al. 2024). Thus, magnetic activity cycles of either component represent one possible explanation for the periodic variation. We also explored the relationship between the successive O' Connell effect from TESS data and the $O - C$ trend, finding no correlation between them, consistent with investigations on other binaries (Koju & Beaky 2015; Pi et al. 2019).

To understand the evolution and magnetic activity of the contact binary EF Boo, continued photometric monitoring is necessary to confirm these behaviors in the light curves and orbital period in the future.

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Note: Figure translations are in progress. See original paper for figures.