The Measurement of Dynamic Tidal Contribution to Apsidal Motion in Heartbeat Star KIC 4544587

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Abstract

Apsidal motion is a gradual shift in the position of periastron. The impact of dynamic tides on apsidal motion has long been debated, because the contribution could not be quantified due to the lack of high-quality observations. KIC 4544587 with tidally excited oscillations has been observed by Kepler high-precision photometric data based on long-time-baseline and short-cadence schema. In this paper, we compute the rate of apsidal motion that arises from the dynamic tides as 19.05 ± 1.70 mrad yr⁻¹ via tracking the orbital phase shifts of tidally excited oscillations. We also calculate the procession rate of the orbit due to the Newtonian and general relativistic contribution as 21.49 ± 2.8 and 2.4 ± 0.06 mrad yr⁻¹, respectively. The sum of these three factors is in excellent agreement with the total observational rate of apsidal motion 42.97 ± 0.18 mrad yr⁻¹ measured by eclipse timing variations. The tidal effect accounts for about 44% of the overall observed apsidal motion and is comparable to that of the Newtonian term. Dynamic tides have a significant contribution to the apsidal motion. The analysis method mentioned in this paper presents an alternative approach to measuring the contribution of the dynamic tides quantitatively.

Unified Astronomy Thesaurus concepts: Apsidal motion (62); Asteroseismology (73); Binary stars (154); Tidal interaction (1699)

1. Introduction

In close binary systems with eccentric orbits, the tidal and rotational distortions of the components induce mass redistributions in the star from spherical symmetry. The nonspherical gravitational field leads to a gradual shift in the position of periastron (\(\omega\)), known as apsidal motion (\(\dot{\omega}\); Claret & Gimenez 1993; Zasche et al. 2020). The analog to apsidal motion is the well-known effect as Mercury’s perihelion advance in the solar system.

Theoretically two different contributions are thought to devote additively to this precession: a classical or Newtonian term (NT, \(\dot{\omega}_{NT}\); Sterne 1939) arising from the distributions of density within components, and a general relativistic (GR) correction (\(\dot{\omega}_{GR}\); Shakura 1985) that is on account of the space distortion in a strong gravitational field. Near the periastron, the tidal distortion leads to a perturbation of the external gravitational field, which in turn contributes to the apsidal motion and is called the contribution of the dynamic tides (\(\dot{\omega}_{DT}\); Smeyers et al. 1991). The NT and the GR term have been widely confirmed (Splaver et al. 2002; Constantin 2013; Manzoori 2020). Unfortunately, the scenario of dynamic tides was not always fulfilled (Claret & Willems 2002; Smeyers 2005; Pavlovski et al. 2011; Claret 2019) because tidal contribution could not be quantified due to the lack of high-quality observations.

Heartbeat stars are close eccentric binary stars in short orbital periods with tidal distortions (Thompson et al. 2012). Most of the heartbeat stars undergo periodic tidal force throughout the orbit, which causes dynamic tides and induces tidally excited oscillations (TEOs) simultaneously (Shporer et al. 2016; Fuller 2017). Tidal effects are most significant at the position of periastron causing a prominent distorting of the shape of the light curve, known as a “heartbeat” signature.

The Kepler space telescope (Borucki et al. 2010) provides us long-time-baseline and high-precision photometric data that are ideal for the study of the dynamic tides in heartbeat stars (Dimitrov et al. 2017; Cheng et al. 2020), in particular the short-cadence (58.89 s) data. Over 170 heartbeat stars have been discovered in Kepler data (Kirk et al. 2016; Gaulme & Guzik 2019), and some targets have been analyzed in detail, such as KOI-54, the prototypical heartbeat star (Welsh et al. 2011; O’Leary & Burkart 2014); KIC 8164262 (Hambleton et al. 2018); KOI-3890 (Kuszlewicz et al. 2019); KIC 4142768 (Guo et al. 2019); and KIC 5006817 (Mere et al. 2021).

More recently, an excellent study for the relationship between the position of periastron and the pulsation phase of TEOs has been discussed in Guo et al. (2020). However, the position of periastron that they discussed was a fixed value, that is, \(\omega\) did not change in eccentric orbits. Here, we focus on the precession of periastron \(\dot{\omega}\) and investigate the dynamic tidal contribution to the rate of apsidal motion quantitatively. The changes in the position of periastron cause the changes in the induced time of TEOs. Therefore, the measurement of the time delay of TEOs in heartbeat stars makes it possible to probe the relationship between the tidal effect and the apsidal motion.
KIC 4544587 is an eccentric close binary system with dynamical tides that presents TEOs. On account of the nature of stellar oscillations and apsidal motion, we deduce the rate of apsidal motion arising from dynamic tides. This paper is organized as follows. In Section 2 we describe the observations of KIC 4544587 including Kepler photometry data and the absolute parameters of this system. In Section 3, the short-cadence photometry data are used for light-curve analysis. Measuring the primary and secondary mid-eclipse times is described in Section 3.1, and the principle of TEOs’ phase delay is presented in Section 3.2. Based on the measurement of eclipse timing variations, we calculated the total apsidal motion rate of KIC 4544587 in Section 4.1. NT and GR contributions relied on accurate absolute parameters are calculated in Section 4.2. Finally, we use the shifts of dynamic tide to derive the contribution of apsidal motion caused by tidal effects in Section 4.3. The main results and discussions are summarized in Section 5.

2. The Observations of KIC 4544587

2.1. Kepler Photometry

KIC 4544587 has a Kepler magnitude $K_p = 10.8$. The photometric data include long cadence during quarters 0–17 and short cadence during quarters 3.2, and 7–10. The short-cadence data with 58.89 s sampling have the advantage of increasing frequency resolution. High-frequency resolution enables the accurate identification of tidally excited oscillations that are present in this target. Consequently, short-cadence data during quarters 7–10 are used to analyze the TEOs and eclipse timing variations. As a preprocessing step, we detrended and normalized these data by fitting a first- or second-order polynomial to individual segments of data separated by gaps, which were caused by spacecraft rolls or safe mode events. Figure 1 shows the orbital phase of the detrended light curve and its magnified image.

2.2. The Absolute Dimensions

Accurate absolute dimensions are necessary for reliable interpretation of the apsidal motion. Thanks to the excellent work of Hambleton et al. (2013), we can easily retrieve the basic information related to KIC 4544587. The atmospheric parameters for the components, such as the effective temperatures and surface gravities, are derived from the disentangled spectra data. The projected rotational velocities are determined by the optimal fitting of the metal lines. Spectral information shows that the components of the binary system are all A-type stars. The orbital period and time of primary minimum are determined with the short-cadence data (quarters 3.2, 7, and 8) using KEPHEM software (Prša et al. 2011), and the geometrical configuration and stellar parameters are obtained by fitting the light curve for quarters 7–8 with the PHOEBE package (Prša & Zwitter 2005). We summarize the parameters in Table 1.

The results of the pulsational analysis are also presented in Hambleton et al. (2013). KIC 4544587 includes at least one pulsating component. Asteroseismology analysis revealed 31 pulsating modes, including 23 self-excited pressure and gravity modes, and 8 tidally excited modes that are multiples of the orbital frequency. The maximum TEO frequency is 44.31 day$^{-1}$, which corresponds to 97 times the orbital frequency. A first look by Hambleton et al. (2013) suggested that the rapid apsidal motion 43.06 mrad yr$^{-1}$ may be partially attributable to the resonant oscillations.

3. Light-curve Analysis

3.1. Measuring Mid-eclipse Times

We use a polynomial fit to determine the mid-eclipse times as described in Rappaport et al. (2013) and Yang et al. (2015). The analytic function does not represent a physical model, but rather searches a local minimum flux $F_0$ on the eclipsing binary light curve. The polynomial template defines the stellar flux $F$.
as a function of time \( t \) by
\[
F = \alpha (t - t_0)^2 + \beta (t - t_0)^4 + F_0,
\]
where \( \alpha \) and \( \beta \) are the coefficients, and \( t_0 \) is the mid-eclipse time. By fitting the mean phased shape of all eclipse light curves, we obtain the theoretical template that depends on the four parameters \( \alpha, \beta, t_0, \) and \( F_0 \). Next, the whole light curve is divided into many individual eclipse parts for each epoch, i.e., the number of orbits \( N \). All the other parameters except \( t_0 \) are fixed to be the same as the theoretical template. Then, the fitted polynomial parameter \( t_0 \) is used to determine a more accurate observed mid-eclipse time in each individual eclipse. We take this approach to find the horizontal shifts of the primary and secondary eclipses, as shown in the top and middle panels of Figure 2, respectively. The x-axis is the orbital phase, while the y-axis is the mid-eclipse phase of orbit. The time of primary minimum in Barycentric Julian Days (BJD) is chosen to be 2455462.006137, which is consistent with the choice made in Hambleton et al. (2013), and we set the primary eclipse as orbital phase 0.

### 3.2. Measuring Phase Delay of TEOs

The relationship between the pulsation intrinsic phase \( \varphi_I \) of TEOs and the argument of periastron \( \omega \) has been well discussed in Guo et al. (2020, his Equation (3)). Here we focus on the induced time delay of the pulsation phase due to the change of periastron position. At the time of periastron passage, the tidal forces induce pulsation modes with intrinsic phase \( \varphi_I \). When a TEO with frequency \( \nu \) dominates the dynamical tidal response, a sinusoidal luminosity fluctuation will be generated as the form (Fuller 2017)
\[
\Delta L \propto \sin[2 \pi \nu(t - t_p) + \varphi_I],
\]
where \( t_p \) is the passing time of periastron. If the position of periastron has a small displacement, the tidally induced pulsations will be postponed for the time \( t' \), and the luminosity fluctuation then becomes
\[
\begin{align*}
\Delta L &\propto \sin[2 \pi \nu(t - t_p + t') + \varphi_I] \\
&= \sin[2 \pi \nu(t - t_p) + \varphi_I + \varphi_D],
\end{align*}
\]
with \( t' \) being the time of periastron displacement and accordingly \( \varphi_D \) being the delayed phase of pulsation due to the delay of induced time. In turn, the measurements of \( t' \) can be reversely deduced from the delayed phase \( \varphi_D \) of TEOs.

The delayed phase \( \varphi_D \) is proportional to the frequency of TEOs. In order to get \( \varphi_D \) accurately, we choose the maximum TEO frequency 44.31 day\(^{-1}\) to track the pulsation phase of the light curve. The prescription of the phase modulation method (Murphy et al. 2014) is applied to this specific measurement. In practice, we divide the entire light curve into \( N \) short segments according to each epoch, and then calculate the frequency of each segment in the Fourier transform. The peak frequency closest to 44.31 day\(^{-1}\) is selected. Subsequently, a least-squares fit at the peak frequency is carried out for each segment. The fitting model is a sine function that includes phase as a free parameter. Finally, the measured delayed phase \( \varphi_D \) and its uncertainty are directly obtained from the fitting procedure. In this analysis, only the out-of-eclipse light curve is considered in order to decrease the contamination of orbital frequency.

We emphasize that the intrinsic phase \( \varphi_I \) of TEOs is not of concern here. Instead, we focus on the delayed phase \( \varphi_D \) that reflects the changes of orbital phase. To illustrate the change of the delay phase \( \varphi_D \) on orbit, we arbitrarily choose the obvious curves and have plotted them in Figure 3. Taking the primary

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**Table 1**

| System | Primary | Secondary |
|---|---|---|
| Mass \((M_\odot)\) | 1.98 ± 0.07 | 1.60 ± 0.06 |
| Radius \((R_\odot)\) | 1.76 ± 0.03 | 1.42 ± 0.02 |
| \(T_{\text{eff}}\) (K) | 8600 ± 100 | 7750 ± 180 |
| log g \((\text{cgs})\) | 4.241 ± 0.009 | 4.33 ± 0.01 |
| \(v \sin i\) (km s\(^{-1}\)) | 86.5 ± 1.3 | 75.8 ± 1.5 |

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**Figure 2.** Top and middle panels are the orbital phases of the primary and the secondary mid-eclipse times (Section 3.1), respectively. The opposing direction of the primary and the secondary mid-eclipse phases demonstrates a classical apsidal motion. Bottom panel depicts the shifts of dynamic tides in units of orbital phase (see the details in Section 3.2).
minimum eclipse as the reference point and fixing it at orbital phase $0$ (inset (A)), the orbital phase of the light curve for epochs $N = 7, 85,$ and $163$ were plotted by red, green, and blue lines, respectively. These lines represent the early, middle, and late stages of the orbit. It can be seen from inset (B) that the position of the secondary eclipse has significant horizontal shifts. The total precession rate of apsidal motion is deduced from the spacing between the primary and secondary eclipses, and the details are described in Section 4.1.

The horizontal shift of the dynamic tides is displayed in inset (C). The specific value of dynamic tides shift is obtained by the delayed phase $\varphi_D$ of TEOs and then converted to the orbital phase:

$$\phi_{\text{TEO}} = \phi_{\text{TEO}_0} + \Delta \phi_{\text{TEO}} = \left( t_p + t' \right) / P_a = \left( t_p + \frac{\varphi_D}{2 \pi P} \right) / P_a,$$

where $P_a$ is the anomalistic period and $\varphi_D$ is measured by the phase modulation method. $\phi_{\text{TEO}_0}$ is the periastron passing time in units of orbital phase. To avoid confusion, we label the pulsation phase as $\varphi$ and the orbital phase as $\phi$, respectively. This approach produced a set of orbital phases $\phi_{\text{TEO}}$ as a function of epoch. The measurements of $\phi_{\text{TEO}}$ are shown in the bottom panel of Figure 2.

4. The Argument of Periastron

4.1. Determining Total Rate of Apsidal Motion by Mid-eclipse Times

The eclipse minima of the light curve in KIC 4544587 are narrow and deep enough to permit getting accurate mid-eclipse times, which can be used to precisely determine the total effect of apsidal motion in this binary system. The method presented by Giménez & Bastero (1995) is often used to calculate the apsidal motion rate in eclipsing binary systems. This method assumes that the binary system has a nonzero eccentricity $e$ and the argument of periastron $\omega$ is precessing uniformly. The mid-eclipse time of the primary $t_{\text{pri}}$ and the secondary $t_{\text{sec}}$ are expressed as (Giménez & Bastero 1995; Yee et al. 2020)

$$t_{\text{pri}}(N) = t_0 + NP_a - \frac{P}{\pi} \cos \omega(N),$$

$$t_{\text{sec}}(N) = t_0 + NP_a + \frac{P}{\pi} \cos \omega(N) + \frac{P}{2},$$

$$\omega = \omega_0 + N\dot{\omega},$$

where $P = P_a(1 - \dot{\omega}/2\pi)$ is the sidereal period, and $\dot{\omega}$ is the rate of apsidal motion in units of rad per cycle. Subtracting Equation (6) from Equation (7) generates

$$t_{\text{sec}} - t_{\text{pri}} = \frac{2eP}{\pi} \cos \omega + \frac{P}{2}.$$  

With some rearrangements the time interval between primary and secondary mid-eclipses gives the relationship of $e$ and $\omega$ as

$$e \cos \omega = \frac{\pi}{2} \left( t_{\text{sec}} - t_{\text{pri}} - \frac{1}{2} \right) = \frac{\pi}{2} \left( \phi_{\text{sec}} - \phi_{\text{pri}} - 0.5 \right).$$

The parameters on the right-hand side of Equation (10) have been measured from the light curve (Figure 2). Eccentricity has a major impact on solving the argument of periastron. Since the photometric light curve used in this analysis is different from those of Hambleton et al. (2013), here we use the PHOEBE package (Prša & Zwitter 2005; Conroy et al. 2020), which contains the tidal distortion effects to determine the orbit eccentricity again. The acquired eccentricity $e = 0.252$ is fixed in the following analysis, because the perturbation of eccentricity is on a much longer timescale than the dynamical motions considered here. Finally, the observed value of $\omega$ is obtained through the solution of Equation (10). The results are marked by blue dots as shown in Figure 4. The increase of $\omega$ is a remarkable manifestation of the apsidale line precession. By using Equation (8) to fit the values of $\omega$, the total rate of apsidal motion is determined as $\dot{\omega}_{\text{sec}} = 42.97 \pm 0.18 \text{ mrad yr}^{-1}$ which is in agreement with the literature value $43.06 \pm 0.02 \text{ mrad yr}^{-1}$ reported by Hambleton et al. (2013).
The Astrophysical Journal, 922:37 (7pp), 2021 November 20

Figure 4. Depicted are the position shift of periastron measured by mid-eclipse times (blue dots) and tidally excited oscillations (red dots), respectively. The slope of periastron arguments caused by dynamic tides is less than that measured by mid-eclipse times, implying that the dynamic tides partially contribute to the total of apsidal motion.

4.2. The Contributions of the Newtonian Term and General Relativistic Corrections

In the theoretical framework of apsidal motion, the total rate is divided into two parts: the Newtonian effects and the GR corrections. Supposing the stellar rotation axis is aligned with the normal of the orbital plane, the rate of apsidal motion contributed by the NT takes the form of (Shakura 1985; Rosu et al. 2020)

\[
\omega_{\text{NT}} = \frac{2\pi}{P_{\text{orb}}} \left\{ 15h(e) \left( \frac{k_{2,1}}{R_1 a} \right)^5 + k_{2,2} \left( \frac{R_2}{a} \right)^5 \right. \\
+ g(e) \left[ \frac{1}{q} \left( \frac{R_1}{a} \right)^5 \left( \frac{P_{\text{orb}}}{P_{\text{rot},1}} \right)^2 \right] \left[ \frac{R_2}{a} \right]^5 \left( \frac{P_{\text{orb}}}{P_{\text{rot},2}} \right)^2 \left. \right\},
\]

\[
h(e) = \frac{1}{(1 - e^2)^2} \left( \frac{1 + 3e^2/2 + e^4/8}{1 - e^2} \right),
\]

\[
g(e) = \frac{1}{(1 - e^2)^2},
\]

where the subscripts “1” and “2” refer to the primary and the secondary stars, respectively. \( R \) is the stellar radius. \( P_{\text{rot}} \) is the rotational period. \( P_{\text{orb}} \) is the orbital period, and \( q = m_1/m_2 \) is the mass ratio. In this paper, we only consider the perturbations arising from the second-order harmonic distortions (Sterne 1939) of the gravitational potential; the term of internal structure constant is denoted by \( k_2 \).

Using the stellar evolution models computed by Claret (2004) we retrieve the internal structure constants as \( k_{2,1} = 4.087 \times 10^{-3} \) and \( k_{2,2} = 4.078 \times 10^{-3} \) for the primary and secondary components, respectively, which correspond to A-type stars (Hambleton et al. 2013). Using the binary parameters of KIC 4544587 along with its uncertainties, we obtain a value of \( \omega_{\text{NT}} = 21.49 \pm 2.80 \text{ mrad yr}^{-1} \) for the Newtonian contribution to the total rate of apsidal motion. It is worth noting that the estimated value \( \omega_{\text{NT}} \) here is the upper limit because we assume that the stellar rotation axis is parallel to the orientation of the orbital angular momentum in the first place.

The GR correction to the total rate of apsidal motion is given by the expression (Shakura 1985; Rosu et al. 2020)

\[
\omega_{\text{GR}} = \frac{2\pi}{P_{\text{orb}}} \frac{3G(m_1 + m_2)}{c^2 a(1 - e^2)} \left( \frac{P_{\text{orb}}}{P_{\text{rot},1}} \right)^{5/3} \left( \frac{P_{\text{orb}}}{P_{\text{rot},2}} \right)^{2/3},
\]

where \( G \) is the gravitational constant, \( c \) the speed of light, and \( a \) the semimajor axis. Using the observed parameters of the binary system, we figure out \( \omega_{\text{GR}} \) as \( 2.40 \pm 0.06 \text{ mrad yr}^{-1} \). Therefore, the contribution of the sum of the Newtonian effects and the GR corrections is 23.89 mrad yr\(^{-1}\), which is significantly less than the total rate of 42.97 mrad yr\(^{-1}\), indicating that there must be some missing factors influencing the apsidal motion.

First, the third light contamination value for KIC 4544587 is estimated to be 0.019. Note that 1 implies complete contamination and 0 implies no contamination of the CCD pixels. This contamination value suggests that KIC 4544587 suffers no impact from the third body. Second, the rotation axis of the primary more or less misaligns with the normal of the orbital plane (Khalilullin & Khalilullina 2007; Pavlovski et al. 2011; Schmitt et al. 2016). If the angle between the rotation axis and the orbit plane is taken into account, the contributions of the NT will be less than \( 21.49 \pm 2.8 \text{ mrad yr}^{-1} \). Such an angle will increase the deviation, so it cannot be caused by misalignments between rotation and orbit axes. Finally, the internal structure constants of each component are consistent with their spectral types. The internal structure constants are unlikely to make such a big deviation.

4.3. The Contribution of Dynamic Tides to Apsidal Motion

In this section, we demonstrate how to use the orbital phase of TEOs (\( \phi_{\text{TEO}} \)) to determine the rate of apsidal motion that arose from dynamic tides. It is well known that the geometrical change of the binary orbit causes the shift of pulsation phases. This section is an inverse derivation of this idea. We convert the delayed phase \( \phi_D \) of TEOs to the tiny shift \( \Delta \phi_{\text{TEO}} \) of the orbital phase (Equation (5)), and here derive back the changes of the periastron position due to tidal effects. Note that the derivation in this section is all about orbital phases.

Figure 5 illustrates the geometry of the elliptical orbit for an eccentric binary system (Giménez & Garcia-Pelayo 1983; Matson et al. 2016). The components orbit the center of mass and attain the periastron (marked by the star) at the right-hand side of the diagram. Supposing the line of sight from which we observe the binary is from the lower right, then the primary eclipse (marked by the square) occurs when the primary star is behind the secondary star along the line of sight, and the secondary eclipse occurs at the location marked by the diamond.
The Astrophysical Journal, 922:37 (7pp), 2021 November 20

5. Discussion and Conclusions

In previous studies, the lack of high-precision consecutive photometric data makes it difficult to accurately determine the contributions of dynamic tides on the apsidal motion from an observational point of view. Observations lasting for a few years are precious for the investigation of tidally excited oscillations. It allows us to measure the dynamic tides contribution to apsidal motion by tracing the delayed phase of TEOs. In this paper, we use the approximate 1 yr long time baseline data from the NASA Kepler space telescope to demonstrate that the dynamic tides contribution to apsidal motion is definitely present in an eccentric binary system KIC 4544587.

Based on the high-precision Kepler photometric data and the accurate absolute dimensions of KIC 4544587, we infer the contributions of NT $\omega_{NT}$, GR correction $\omega_{GR}$, and dynamic tides $\omega_t$ to the total rate of apsidal motion are 21.49 $\pm$ 2.80, 2.40 $\pm$ 0.06, and 19.05 $\pm$ 1.70 mrad yr$^{-1}$, respectively. By considering the luminosity fluctuation with respect to periastron, we are accounting for the rotation of the orbit due to the Newtonian and GR contributions. The sum of these three factors of $42.94 \pm 4.56$ mrad yr$^{-1}$ is in excellent agreement with the total rate of apsidal motion $42.97 \pm 0.18$ mrad yr$^{-1}$ measured by mid-eclipse times. Furthermore, the consistency suggests that the NT is up to its upper limit, i.e., implies that the stellar rotation axis is aligned with the normal of the orbital plane in this eccentric binary system with tidally excited oscillations.

Comparing the different terms in the apsidal moment of this system, we find that the contribution of the NT plays a dominant role in total apsidal motion, accounting for about 50%, while the tidal effect accounts for about 44% and the GR correction for about 6%.

The NT itself is the sum of effects induced by the density distribution of stars and the tidal deformation. Due to the lack of high-quality observational data in previous studies, the effects of dynamic tides were attributed to the Newtonian contribution. In other words, tidally excited oscillations were considered as factors of stellar internal structure and used to deduce the stellar internal structure constants $k_2$ (Sirotkin & Kim 2009). However, when the tidal force of a companion star is large enough to excite the stellar oscillation modes in component stars, the contribution of dynamic tides will be comparable to that of NTs. In this scenario, the tidal effects can no longer be attributed to the stellar internal structure, but should be considered carefully. In previous literature, the theoretical rate of apsidal motion for some targets deviated from the observed rate (Giménez 2007), perhaps because the contribution of dynamic tides was not considered sufficiently. The analysis method mentioned in this paper presents an alternative approach to measuring the contribution of dynamic tides quantitatively.

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Ou et al.
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