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Discovery of Tidally Perturbed Pulsations in the Eclipsing Binary U Gru: A Crucial System for Tidal Asteroseismology

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Abstract

The interior physics of stars is currently not well constrained for early-type stars. This is particularly pertinent for multiple systems, as binary interaction becomes more prevalent for more massive stars, which strongly affects their evolution. High-precision photometry from the *Transiting Exoplanet Survey Satellite* (*TESS*) mission offers the opportunity to remedy the dearth of observations of pulsating stars that show evidence of binary interaction, specifically pulsating mass-accreting components of semi-detached Algol-type eclipsing binary (oEA) systems. We present the *TESS* light curve of the circular eclipsing binary system U Gru (TIC 147201138), which shows evidence of free heat-driven pressure modes and a series of tidally perturbed pressure modes. We highlight the asteroseismic potential of studying pulsating stars in binary systems, and demonstrate how tidal asteroseismology can be applied to infer the influence of binary interaction on stellar structure.

Key words: asteroseismology – stars: evolution – stars: individual (U Gru) – stars: massive – stars: oscillations – stars: rotation

1. Introduction

For intermediate- and high-mass stars, the incidence of multiplicity and the interaction of stars within binary systems have a substantial impact on their structure and evolution (Sana et al. 2012; Duchêne & Kraus 2013; De Marco & Izzard 2017; Moe & Di Stefano 2017). However, the effects of binary interaction remain largely unconstrained in stellar models, owing to a lack of systems to characterize and test theoretical predictions. Specifically, the consequences of deformation from sphericity, mass transfer, deviation from synchronicity, and tidally induced or perturbed stellar oscillations strongly influence the evolution of stars in multiple systems (Zahn 1975; Kumar et al. 1995; Willems & Aerts 2002; Aerts & Harmanec 2004; Ogilvie 2014; MacLeod et al. 2019).

By means of asteroseismology—the study of stellar pulsations—the interior physics of predominantly single stars covering a range in mass and age in the Hertzsprung–Russell (HR) diagram has been probed (Chaplin & Miglio 2013; Aerts 2015; Hekker & Christensen-Dalsgaard 2017). Stellar pulsations come in two main flavors based on the dominant restoring force: pressure (p) and gravity (g) modes. The former typically have pulsation periods of the order of hours and predominantly probe the stellar envelope, whereas the latter have pulsation periods of the order of days and probe the near-core region (Aerts et al. 2010). The success of asteroseismology has revealed the internal rotation profiles of tens of intermediate-mass main-sequence stars (Aerts et al. 2017) and thousands of red giant stars (Mosser et al. 2012; Gehan et al. 2018), which demonstrate that a more efficient angular momentum transport mechanism is needed than is currently included in evolutionary models of single stars (Aerts et al. 2019).

Ground-based photometry is usually sufficient to detect and measure the period of an eclipsing binary system, but asteroseismic studies require continuous, high-precision, and long-term photometric time series to extract and identify pulsation modes frequencies (Aerts et al. 2010). The potential of combining binary and asteroseismic modeling was recently exemplified by Guo et al. (2016, 2017) and Johnston et al. (2019), yet few pulsating eclipsing binary systems have suitable space photometry to perform robust modeling. The application of tidal asteroseismology using self-excited free pulsations perturbed by tidal forces or pulsations driven by tidal forces within a binary system offers a unique methodology for directly constraining the impact of tides on stellar structure and evolution.

More commonly known are tidally induced pulsations in "heartbeat stars," which are driven by resonances at exact orbital harmonics caused by the temporary tidal distortion at close periastron passage (Welsh et al. 2011; Thompson et al. 2012). Approximately 170 of these systems are known (Prša et al. 2011; Kirk et al. 2016),[5] and modeling has provided insight into their interior structure (Welsh et al. 2011; Hambleton et al. 2013, 2018; Beck et al. 2014; Smullen & Kobulnicky 2015; Fuller 2017). An example of such an pulsating eccentric binary system is KIC 4544587, which also contains tidally split p modes (Hambleton et al. 2013).

On the other hand, tidally perturbed pulsations, which are self-excited free oscillation modes shifted from their eigenfrequencies due to tidal forces, the tidal deformation of the stellar structure, asynchronous rotation, or some combination thereof, lack firm observational characterization. Although a theoretical framework has been developed to investigate tidally perturbed pulsations (see Cowling 1941; Polfliet & Smeyers 1990; Smeyers et al. 1998), there are few candidate binary systems known to exhibit such variability. More discoveries of eclipsing binary systems with at least one star

[5] Binary catalog: http://keplerEBs.villanova.edu.

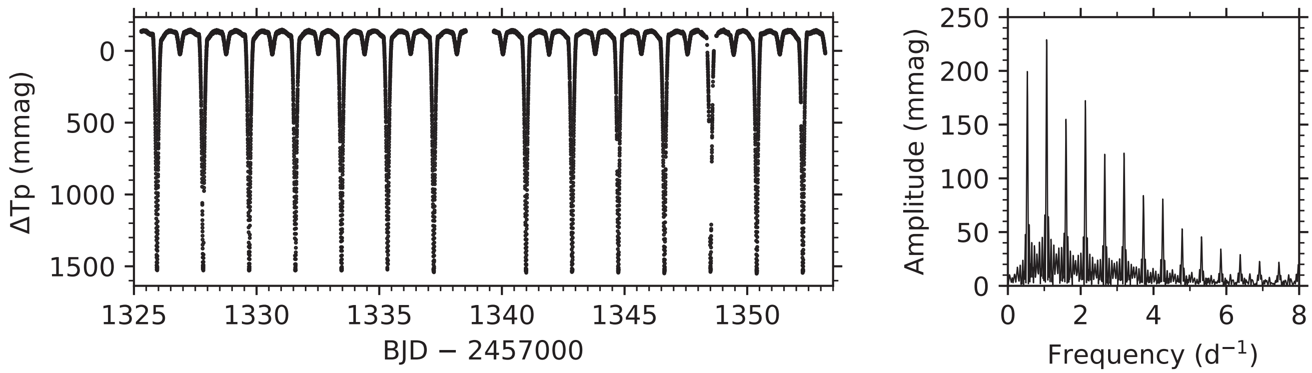

Figure 1. Left: *TESS* light curve of the pulsating Algol system U Gru (TIC 147201138). Right: amplitude spectrum showing the low-frequency orbital harmonic series associated with the eclipses in the light curve.

with tidally perturbed pulsation modes are clearly of high value to the improvement and development of tidal and stellar evolution theory.

Promising targets for tidal asteroseismology include Algol-type systems in which the mass-accreting primary exhibits p modes (i.e., oEA systems), having gained a considerable fraction of its mass from an evolved secondary filling its Roche lobe (Mkrtichian et al. 2002, 2004; Tkachenko et al. 2009; Guo et al. 2016, 2017). The prototype of the oEA class, RZ Cas, revealed strong accretion-driven variability in its pulsation modes (Mkrtichian et al. 2018), thus motivating renewed observational and theoretical efforts to use pulsation modes to probe the influence of angular momentum transfer and tides on stellar structure and rotation. To date, about 70 oEA systems are known. This number is expected to rapidly increase thanks to the high-precision space photometry from the *Transiting Exoplanet Survey Satellite* (*TESS*) mission (Ricker et al. 2015), which is observing a large fraction of the sky with a high photometric precision. In this Letter, we present the *TESS* light curve for the oEA system U Gru (TIC 147201138), which has undergone mass transfer and exhibits tidally perturbed pulsation modes.

2. The Pulsating Eclipsing Binary U Gru—TIC 147201138

In the study of Brancewicz & Dworak (1980), U Gru was identified as a semi-detached eclipsing binary system with a primary of spectral type A5 V and an orbital period of 1.88 days. Furthermore, the photometry of the system allowed Brancewicz & Dworak (1980) to estimate an effective temperature of $T_{\rm eff,\,1} \simeq 8000$ K, a mass of $M_1 \simeq 2\,M_\odot$, and a radius of $R_1 \simeq 2.5\,R_\odot$ for the primary. However, the parameters of the secondary are largely unconstrained.

The target U Gru (TIC 147201138) was observed by the *TESS* mission in its sector 1 and the 2 minute cadence light curve spans 27.9 days. We obtained the light curve provided by the *TESS* Science Team from the Mikulski Archive for Space Telescopes (MAST).[6] A description of the data processing pipeline of the *TESS* light curves is provided by Jenkins et al. (2016). We extracted the times series in Barycentric Julian Date (BJD—2457000), removed obvious outliers, converted the stellar flux into magnitudes, and normalized the light curve to be zero in the mean. The resultant light curve is shown in the left panel of Figure 1, which shows deep flat-bottomed primary and shallow triangular secondary eclipses.

We calculated the amplitude spectrum using a Discrete Fourier Transform (DFT; Deeming 1975; Kurtz 1985), with a zoom of the low-frequency regime shown in the right panel of Figure 1. The Nyquist frequency of the 2 minute *TESS* light curves is approximately 360 days^{-1}, which is far higher than the typical frequency regime of p modes observed in δ Sct stars (i.e., $4 \lesssim \nu \leqslant 70$ days^{-1}; Breger 2000; Bowman & Kurtz 2018), and has the advantage of not introducing significant amplitude suppression of any high-frequency pulsation modes (see Bowman 2017). The precise orbital frequency of U Gru, $\nu_{\rm orb} = 0.531774 \pm 0.000004$ days^{-1} (i.e., $P_{\rm orb} = 1.88050 \pm 0.00001$ days), was determined using a multi-frequency nonlinear least-squares fit to the light curve, which included the orbital frequency and the 35 significant consecutive harmonics that have amplitudes larger than 3σ of the least-squares amplitude error (i.e., $A \geqslant 119\,\mu$mag). We determined the linear binary ephemeris of U Gru using the minimum of the primary eclipse as:

$$\mathrm{BJD_{min}} = 2458325.93900 + (1.88050 \pm 0.00001)^{\rm days} \times E. \quad (1)$$

The same orbital frequency was found if 190 harmonics covering up to 100 days^{-1} were included in the multi-frequency nonlinear least-squares fit. The significance of the harmonics of the orbital frequency above 20 days^{-1} ranges between 1σ and 26σ. As expected, the harmonics are exact multiples of the orbital frequency.

The amplitude spectrum of the residual light curve after subtracting the 190-harmonic multi-frequency fit revealed multiple p mode frequencies, as shown in Figure 2, in which harmonics of the orbital frequency are indicated by the vertical red lines. The most notable variance in the amplitude spectrum of the residuals is a series of frequencies between 21 and 31 days^{-1}, which range in amplitude and are separated by the orbital frequency of the binary system given the frequency uncertainties, yet all are significantly different from integer multiples of the orbital frequency. The harmonics of the orbital frequency in this frequency range are of similar amplitude to the pulsation modes and are significant at 3σ of the least-squares amplitude error. The extracted pulsation-mode frequencies are given in Table 1.

All of the pulsation-mode frequencies in the residual amplitude spectrum in Figure 2 are independent, as they are resolved from a harmonic of the orbital frequency by more than twice the Rayleigh resolution criterion, which is defined as $1/\Delta T = 1/27.88$ days $= 0.036$ days^{-1}. In the sub-panel of

[6] http://archive.stsci.edu/tess/all_products.html

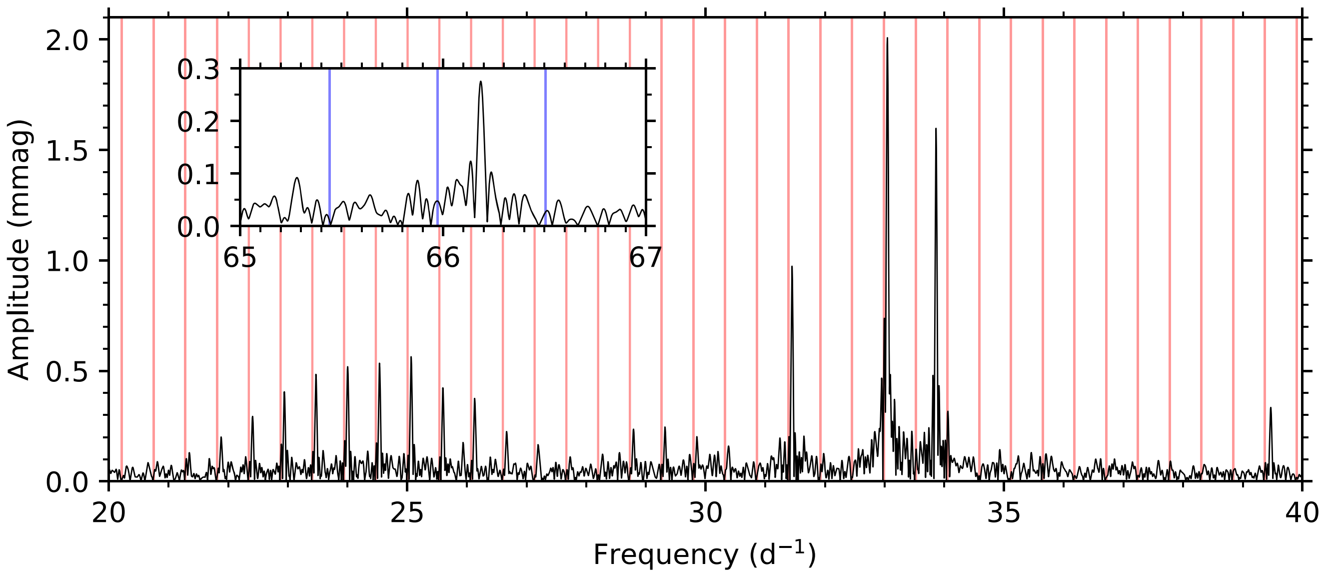

Figure 2. Residual amplitude spectrum after pre-whitening the orbital harmonics (denoted as vertical red lines in the main panel and blue lines in the sub-panel for clarity) in the *TESS* light curve of U Gru revealing pulsation-mode frequencies.

Table 1
Frequencies, Amplitudes, and Phases of the Significant Pulsation Modes in U Gru

Frequency (days^{-1})	Amplitude (mmag)	Phase (rad)	S/N	i	$\nu - i\,\nu_{\rm orb}$ (days^{-1})
21.8802 ± 0.0029	0.217 ± 0.032	0.46 ± 0.15	4.27	41	0.078 ± 0.004
22.4077 ± 0.0021	0.296 ± 0.032	−2.88 ± 0.11	4.92	42	0.073 ± 0.003
22.9411 ± 0.0015	0.413 ± 0.032	0.15 ± 0.08	6.03	43	0.075 ± 0.002
23.4696 ± 0.0013	0.490 ± 0.032	−3.13 ± 0.07	6.26	44	0.072 ± 0.002
24.0022 ± 0.0012	0.520 ± 0.032	−0.03 ± 0.06	6.37	45	0.072 ± 0.002
24.5349 ± 0.0012	0.545 ± 0.032	2.95 ± 0.06	6.37	46	0.073 ± 0.001
25.0644 ± 0.0011	0.564 ± 0.032	−0.41 ± 0.06	6.75	47	0.071 ± 0.001
25.5979 ± 0.0015	0.417 ± 0.032	2.59 ± 0.08	5.72	48	0.073 ± 0.002
26.1303 ± 0.0016	0.381 ± 0.032	−0.69 ± 0.08	5.70	49	0.073 ± 0.002
26.6644 ± 0.0028	0.225 ± 0.032	2.26 ± 0.14	4.33	50	0.076 ± 0.003
27.1966 ± 0.0040	0.155 ± 0.032	−1.37 ± 0.21	3.51	51	0.076 ± 0.004
27.7289 ± 0.0057	0.109 ± 0.032	0.30 ± 0.30	2.72	52	0.077 ± 0.006
28.2758 ± 0.0061	0.103 ± 0.032	−2.95 ± 0.32	2.44	53	0.092 ± 0.006
28.7910 ± 0.0025	0.246 ± 0.032	−0.78 ± 0.13	3.97	54	0.075 ± 0.003
29.3180 ± 0.0025	0.247 ± 0.032	2.16 ± 0.13	4.12	55	0.071 ± 0.003
29.8512 ± 0.0035	0.181 ± 0.032	−1.34 ± 0.18	3.12	56	0.072 ± 0.004
30.3800 ± 0.0037	0.167 ± 0.032	1.69 ± 0.19	2.77	57	0.069 ± 0.004
31.4469 ± 0.0006	0.984 ± 0.032	1.01 ± 0.03	8.17	59	0.072 ± 0.001
33.0442 ± 0.0003	1.997 ± 0.032	−2.16 ± 0.02	8.22	62	0.074 ± 0.001
33.8598 ± 0.0004	1.571 ± 0.032	0.95 ± 0.02	8.78	63	0.358 ± 0.001
39.4689 ± 0.0020	0.323 ± 0.032	2.24 ± 0.10	6.72	74	0.112 ± 0.002
66.1853 ± 0.0023	0.276 ± 0.032	0.41 ± 0.12	5.97	124	0.245 ± 0.009

Note. 1σ uncertainties calculated from the multi-frequency nonlinear least-squares fit and the signal-to-noise ratio (S/N) of each pulsation mode in the residual amplitude spectrum are given. The measured frequency difference between an independent pulsation-mode frequency, ν, and the adjacent (lower frequency) harmonic, i, of the orbital frequency, $i\,\nu_{\rm orb}$, is also provided in the last column.

Figure 2, we show a zoom of an isolated frequency at $\nu = 66.1853 \pm 0.0023$ days^{-1}, which is plotted separately for clarity because of the wide range in pulsation-mode frequencies in U Gru. There are no significant frequencies in the residual amplitude spectrum above 40 days^{-1}, except the one at 66.1853 days^{-1}.

The pulsation modes in the residual amplitude spectrum of U Gru were extracted using iterative pre-whitening and optimized using a multi-frequency nonlinear least-squares fit to the residual light curve (Bowman 2017). In total, 19 significant frequencies in the long series of frequencies were extracted from the residual light curve (see Table 1). Although only the first 17 can be considered part of an unbroken series, the final two frequencies, namely the first- and third -highest amplitude frequencies in the residual amplitude spectrum, 31.4469 and 33.0442 days^{-1}, follow the same pattern of being offset from an orbital harmonic. The frequency offset of a pulsation mode from its adjacent (lower frequency) harmonic of the orbital frequency is also provided in Table 1. The average frequency offset from the adjacent orbital harmonic in

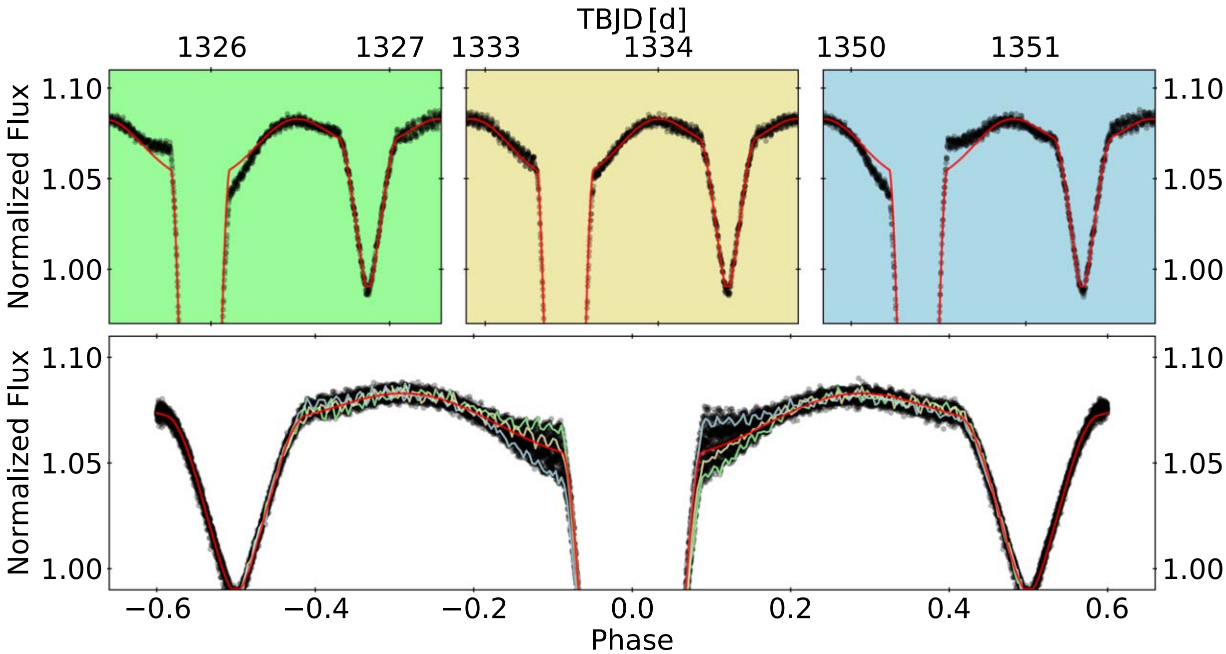

Figure 3. Bottom panel: binary model (red line) and the phase-folded *TESS* observations of U Gru (black points). Top panels: binary model for three sections of the *TESS* data demonstrating how the flux and shape of the light curve at ingress and egress in the primary eclipse changes throughout the observations. The flux offset is largest at the start (green panel) and end (blue panel) of the *TESS* light curve and reverses symmetry in the middle (yellow panel). The light curves from the three top panels are overplotted in the bottom panel to emphasize the changing flux at ingress and egress of the primary eclipse.

the long series of modes is 0.074 days^{-1}, and that deviation from a constant spacing is significant for several frequencies at the $1-\sigma$ level. For example, the pulsation frequency at 28.2758 days^{-1} has a significantly larger offset of 0.092 ± 0.006 days^{-1} from 53 ν_{orb}.

Furthermore, the amplitude spectrum of the residuals shown in Figure 2 contains additional independent pulsation-mode frequencies that cannot be associated with the series of frequencies offset from the orbital harmonics, and represent independent p modes self-excited by the opacity mechanism (Breger 2000; Aerts et al. 2010). Hence, none of the pulsation-mode frequencies in U Gru are at exact integer harmonics of the orbital frequency and many of them appear to be equally spaced by the orbital frequency of the binary system given the frequency uncertainties of the observations.

3. Discussion

We analyzed the *TESS* light curve of U Gru with the `PHOEBE` eclipsing binary modeling code[7] (Prša & Zwitter 2005) using a semi-detached configuration in which the secondary fills its Roche lobe and an assumption of zero eccentricity. The phase-folded *TESS* data and the binary model are shown as the black points and red line, respectively, in the bottom panel of Figure 3. Binary modeling and the totality of the primary eclipses confirm a near edge-on inclination, and indicate a probable photometric mass ratio of $q \simeq 0.17$, although the latter is unconstrained without spectroscopy. These results support the literature classification of U Gru being an Algol-like system (Brancewicz & Dworak 1980) and validate the discovery that U Gru is a new member of the oEA class of variable stars.

The long series of pulsation modes in U Gru spans more than 17 frequencies, and the offset of these modes from orbital harmonics precludes a scenario in which they are excited in a "heartbeat" scenario. The frequency spacing within the long series of pulsation modes cannot be identified as a large frequency separation—i.e., the difference in frequency of consecutive high radial order modes of the same angular degree—using stellar structure models of single stars and the estimated parameters of both components (Brancewicz & Dworak 1980; Aerts et al. 2010). However, owing to the mass transfer that has occurred and the need for including the effect of tides to stellar structure, estimates of the expected large and small frequency separations are uncertain for such a system. Nonetheless, the discovery of a long series of pulsation modes separated by the orbital frequency of the binary system demonstrates the importance of tides for the component stars of U Gru.

Perhaps the most interesting aspect of U Gru is the changing shape of the light curve at the phase of ingress and egress of the primary eclipse in comparison to the best-fitting binary model, which is demonstrated in Figure 3. In the phase-folded light curve of U Gru, it appears as if the pulsation amplitudes are growing near primary eclipse, but as demonstrated in Figure 3, this is caused by the overplotting of the changing normalized flux at ingress and egress at primary eclipse. Such an effect could be explained by the change in flux caused by a corotating surface feature on a component star within an asynchronous system, but testing this hypothesis must await phase-resolved high-resolution spectroscopy.

We also note that the highest-amplitude pulsation mode in the residual amplitude spectrum at 33.0442 days^{-1} is exhibiting amplitude modulation (see, e.g., Bowman et al. 2016) on a timescale longer than the orbital period. Amplitude modulation of pulsation modes both during the orbital phase and on timescales of hundreds to thousands of days has been inferred in some oEA stars using ground-based data (e.g., RZ Cas; Mkrtichian et al. 2018). Accretion-driven variability and

[7] http://phoebe-project.org/

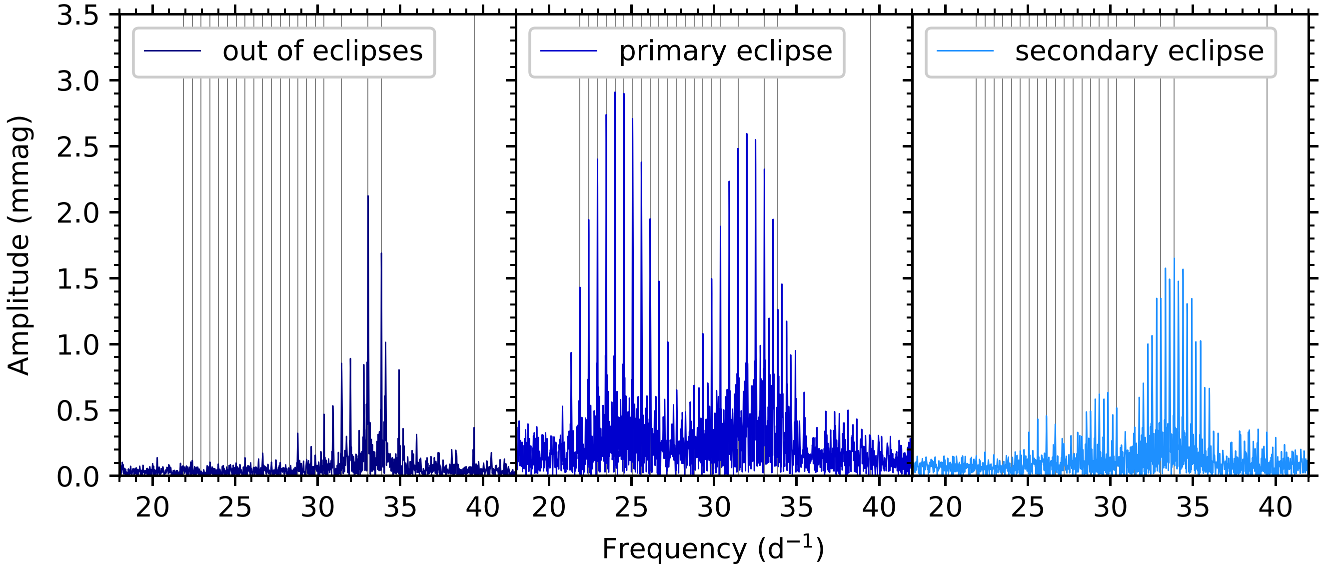

Figure 4. Amplitude spectra of the residual *TESS* light curve (i.e., after subtracting the multi-harmonic binary model) of U Gru at different binary phases (in primary: $-0.09 \leq$ phase ≤ 0.09; in secondary: $0.41 \leq$ phase ≤ 0.59; cf. Figure 3) . The vertical gray lines indicate the frequencies included in Table 1 and identified as significant from the entire light curve.

variable extinction within the semi-transparent circumbinary environment is plausibly the cause of long-term amplitude variability in U Gru, as has been inferred for other oEA systems (e.g., Mkrtichian et al. 2018).

Furthermore, the amplitudes of the pulsation modes comprising the long series of modes in U Gru are also modulated during the binary orbit, as demonstrated in Figure 4, yet the high-frequency independent pulsation modes at 33.8598 days^{-1} and 39.4689 days^{-1} remain approximately constant in amplitude. This demonstrates that the amplitude of the pulsation modes in the long series of modes depends on the binary phase and can be explained by the influence of tides and/or the observed pulsation-mode geometry. The amplitudes of the long series of modes are maximal and form two multiplet structures in the amplitude spectrum during primary eclipse. Therefore, the series of equally spaced pulsation modes may originate in the cooler secondary such that the observed modulation is being caused by geometric cancellation and/or the dependence of pulsation-mode amplitudes on the changing flux ratio of the two components at a specific binary phase.

Synchronicity and circularization are typically assumed for post-mass transfer systems (see Ogilvie 2014; Guo et al. 2016, 2017), but this is not always the case (Escorza et al. 2019). The *TESS* observations of U Gru indicate an eccentricity of nearly, if not exactly, zero, yet the influence of tides is clearly important in U Gru. MacLeod et al. (2019) recently investigated the scenario of tides in asynchronous binaries at the Roche limit using hydrodynamical simulations. The resultant tidal forcing frequency, which is determined by the difference between the orbital and envelope rotation frequencies, may coincide with eigenmode frequencies as the orbit shrinks. It was found that waves of decreasing angular degrees (ℓ) and azimuthal orders (m) are resonantly excited as the system evolves within an unstable mass-transfer scenario (MacLeod et al. 2019). However, such an evolution-based phenomenon is unlikely to be detected in a short light curve spanning only 28 days.

Given these *TESS* observations, we discuss three mechanisms that could be responsible for the rich pulsation spectrum, which require tidal deformation of the pulsation cavity within a star given the circular orbit of U Gru:

(i) Tidally excited modes: the tide-generating potential of the U Gru system excites a long series of consecutive radial order modes, in which the particular range in radial order (n) provides information on the distorted pulsation cavity (Ogilvie 2014). However, the long series of modes are significantly offset from harmonics of the orbital frequency, making this scenario unfavorable.

(ii) Pulsation-mode geometry: the effect of tides acts as a perturbation to the pulsation modes, which causes amplitude modulation with respect to the observer, resulting in a multiplet split by the orbital frequency (see, e.g., Samadi Ghadim et al. 2018). A tidal scenario in which a pulsation mode is trapped to a single hemisphere of the primary and results in amplitude modulation during the orbit and an equally split multiplet in the amplitude spectrum is plausible for U Gru, but such a mechanism does not explain the additional independent pulsation modes. On the other hand, the long series of pulsation modes spaced by the orbital frequency could originate from the secondary, whose pulsation-mode amplitudes are maximal during primary eclipse because of geometric cancellation and/or the dependence of pulsation-mode amplitudes on the changing relative flux ratio at a given binary phase. In this case, U Gru represents a circular eclipsing binary system that contains two pulsating components whose pulsations are influenced by tides.

(iii) Tidally perturbed modes: the observed frequencies are free oscillations that are self-excited by the opacity mechanism, but whose eigenfrequencies are perturbed from the corresponding single-star unperturbed eigenfrequencies because of the tidal deformation of the pulsation cavity (Polfliet & Smeyers 1990; Reyniers 2002; Reyniers & Smeyers 2003a, 2003b).

The detection of a long series of pulsation modes, which are plausibly modes of consecutive radial order and are significantly different from the harmonics of the orbital frequency, in addition to independent, free self-excited p modes, indicates that cases (ii) and (iii) are important in U Gru. Therefore the discovery of such a rich pulsation spectrum in an oEA system such as U Gru offers a unique and exciting prospect for the application of tidal asteroseismology, as the influence of tides can be directly measured from the perturbations to observed pulsation-mode frequencies.

The case for asynchronous rotation being the cause of the tidal torque in a circular binary system will be tested using a spectroscopic measurement of rotation, i.e., $v \sin i$, and the subsequent investigation of the synchronicity parameter in future binary modeling including spectroscopic radial velocities. We are currently gathering the necessary high-resolution spectroscopy to determine accurate stellar parameters for both components and perform robust binary modeling by combining radial velocity measurements with the *TESS* light curve of U Gru. The resultant binary parameters and subsequent asteroseismic modeling will ascertain the most likely overall tidal scenario (C. Johnston et al. 2019, in preparation). The combination of high-precision *TESS* photometry, high-resolution spectroscopy, and forward-seismic modeling will provide quantitative measures of the influence of tides on stellar structure and evolution in a pulsating eclipsing binary system.

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