

DISCOVERY OF TIDALLY-PERTURBED PULSATIONS IN THE ECLIPSING BINARY U GRU: A PIONEERING 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 the more massive the stars and 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 stars that show evidence of binary interaction and mass transfer, specifically eclipsing pulsating Algol (oEA) systems. We present the TESS light curve of the eclipsing binary system U Gru (TIC 147201138), which shows evidence for tidally-perturbed and independent heat-driven pulsation 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.

Keywords: asteroseismology – stars: evolution – stars: massive – stars: eclipsing – stars: oscillations
– stars: rotation

1. INTRODUCTION

For intermediate- and high-mass stars, the incidence of stellar multiplicity and the interaction of stars within binary systems have a substantial impact on their stellar structure and evolution (Sana et al. 2012; Duchêne & Kraus 2013; Moe & Di Stefano 2017; De Marco & Izzard 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. More specifically, the evolutionary consequences of deformation from sphericity, mass transfer, deviation from synchronicity, and tidally induced or perturbed stellar oscillations are all phenomena that strongly influence the evolutionary pathway of stars in multiple systems (Zahn 1975; Kumar et al. 1995; Willems & Aerts 2002; Aerts & Harmanec 2004; Ogilvie 2014; MacLeod et al. 2018).

By means of asteroseismology – the study of pulsations to constrain stellar structure and evolution – astronomers have been able to probe the interior physics of predominantly single stars across a large range in mass and age in the Hertzsprung–Russell (HR) diagram (Chaplin & Miglio 2013; Aerts 2015; Hekker & Christensen-Dalsgaard 2017). The success of asteroseismology is revealed by the measurement of approximately uniform radial rotation in hundreds of main-sequence stars (Aerts et al. 2017), and thousands of red giant stars (Mosser et al. 2012), which indicates that a more efficient angular momentum transport mechanism currently included in evolutionary models is needed within single stars on the main sequence (Aerts et al. 2019). Pulsations come in two main flavors based on the restoring force. Standing waves for which pressure is the dominant restoring force (i.e. sound waves) are called p modes, which typically have pulsation periods of order hours and predominantly probe the stellar envelope. Conversely, standing waves for which gravity (buoyancy) is the restoring force are called g modes, which have

pulsation periods of order days and probe the near-core region (Aerts et al. 2010).

Ground-based photometry is usually sufficient to detect and measure the period of an eclipsing binary system, yet a full characterization of the orbital properties in addition requires radial velocities from spectroscopy. On the other hand 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 exemplified in the recent work by Johnston et al. (2019), yet few pulsating eclipsing binary systems have suitable space photometry to perform robust modeling. For some binary systems, the application of tidal asteroseismology – the study of stellar interiors through the analysis of self-excited pulsations perturbed by tidal forces or pulsations driven purely by tidal forces – offers a unique methodology for directly constraining the impact of tides on stellar structure and evolution.

Although a theoretical framework has been developed to investigate tidally-perturbed pulsations (see Cowling 1941; Polfiet & Smeyers 1990; Smeyers et al. 1998), i.e. pulsation modes influenced by the effects of a tidal torque, there are few candidate binary systems known to exhibit such variability. To date, KIC 10080943 is the only binary system observed using space photometry that comprises two pulsating F stars with g mode period spacing patterns and p modes split by the orbital frequency, which were used to inform asteroseismic modelling (Schmid & Aerts 2016). However, the lack of eclipses in the light curve of KIC 10080943 meant that the inference from asteroseismic modeling of this system was limited (Johnston et al. 2019). Therefore eclipsing binary systems with at least one star with tidally-perturbed pulsation modes are of high value to the improvement and development of tidal theory, and its impact on stellar evolution theory.

More commonly known are the 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)¹, and modeling has provided insight of their interior structure (Welsh et al. 2011; Beck et al. 2014; Smullen & Kobulnicky 2015; Hambleton et al. 2013, 2018; Fuller 2017). On the other hand, tidally-perturbed pulsations, which are self-excited oscillations shifted from their eigenfre-

quencies due to tidal forces, the tidal deformation of the stellar structure, asynchronous rotation or some combination thereof, lack firm observational characterisation. Modeling of these modes provides direct constraints on the influence of tides on stellar structure.

Promising targets for tidal asteroseismology include Algol-type systems in which the mass-accreting primary exhibits δ Sct pulsation 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). The progenitor of the oEA class, RZ Cas, revealed strong accretion-driven variability in its pulsation modes (Mkrtichian et al. 2018), hence motivating the renewed 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 exhibits evidence for having undergone mass transfer and 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 d. Furthermore, photometry of the system allowed Brancewicz & Dworak (1980) to estimate an effective temperature of $T_{\text{eff},1} \simeq 8000$ 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 its 2-min light curve spans 27.9 d. We obtained the 2-min light curves provided by the TESS Science Team from the Mikulski Archive for Space Telescopes (MAST)². A description of the data processing pipeline of the 2-min 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

¹ an up-to-date catalog is available at: <http://keplerEBs.villanova.edu>

² http://archive.stsci.edu/tess/all_products.html

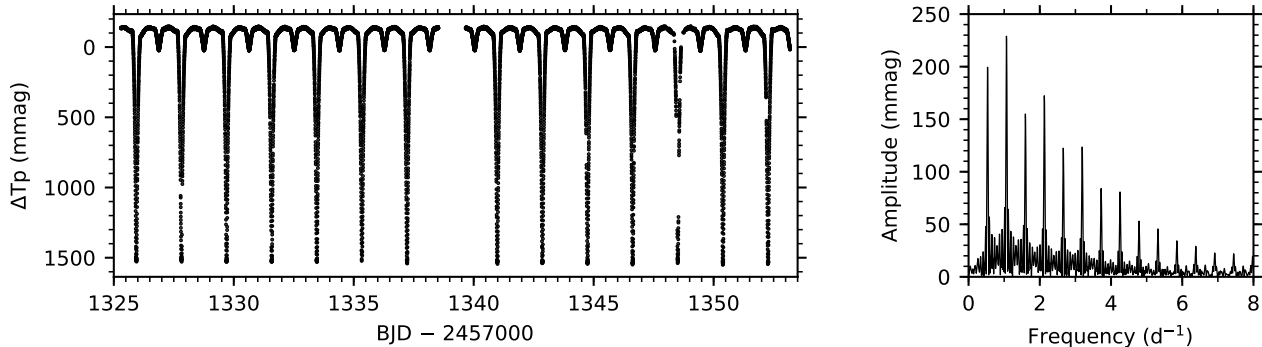


Figure 1. *Left:* TESS light curve of the pulsating Algol system U Gru (TIC 147201138). *Right:* amplitude spectrum showing the low-frequency orbital harmonic series associated with the eclipses in the light curve.

shown in the left panel of Fig. 1, which shows deep primary and shallow secondary eclipses.

We calculated the amplitude spectrum using a Discrete Fourier Transform (DFT; Deeming 1975; Kurtz 1985), with a zoom-in of the low-frequency regime shown in the right panel of Fig. 1. The Nyquist frequency of the 2-min TESS light curves is approximately 360 d^{-1} which is far higher than the typical frequency regime of p modes observed in δ Sct stars (i.e. $4 \lesssim \nu \lesssim 70 \text{ d}^{-1}$; 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, $\nu_{\text{orb}} = 0.531774 \pm 0.000004 \text{ d}^{-1}$ (i.e. $P_{\text{orb}} = 1.88050 \pm 0.00001 \text{ d}$), was determined using a multi-frequency non-linear 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. $A \geq 119 \mu\text{mag}$). We determine the linear binary ephemeris of U Gru using the minimum of the primary eclipse as:

$$\text{BJD}_{\text{min}} = 2458325.93900 + (1.88050 \pm 0.00001)^{\text{d}} \times E. \quad (1)$$

The same orbital frequency is found if 190 harmonics covering up to 100 d^{-1} are included in the multi-frequency non-linear least-squares fit. The significance of the harmonics of the orbital frequency above 20 d^{-1} range between 1σ and 26σ ; the highest amplitude harmonic is at $58\nu_{\text{orb}} = 30.84287 \pm 0.00078 \text{ d}^{-1}$, which has an amplitude of $1001 \pm 39 \mu\text{mag}$. As expected, the harmonics are exact multiples of the orbital frequency given the resolution of the TESS light curve.

The amplitude spectrum of the residual light curve after subtracting the 190-harmonic multi-frequency fit revealed multiple p mode frequencies, as shown in Fig. 2, in which the locations of harmonics of the orbital frequency are indicated by the vertical red lines. The most notable variance in the amplitude spectrum of the resid-

uals is a series of frequencies between 21 and 31 d^{-1} , which range in amplitude but are *approximately* equally split by the orbital frequency of the binary system, yet do not occur at 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 or greater.

We emphasize that all of the pulsation mode frequencies in the residual amplitude spectrum in Fig. 2 are resolved from a harmonic of the orbital frequency by more than twice the Rayleigh resolution criterion, which is defined as $1/\Delta T = 1/27.88 \text{ d} = 0.036 \text{ d}^{-1}$. In the sub-panel of Fig. 2, we show a zoom-in of an isolated frequency at $\nu = 66.1853 \pm 0.0023 \text{ d}^{-1}$, which is plotted separately for clarity because of the wide range in pulsation mode frequencies observed in the residual amplitude spectrum of U Gru. There are no significant frequencies in the residual amplitude spectrum above 40 d^{-1} except the one at 66.1853 d^{-1} .

The pulsation modes in the residual amplitude spectrum of U Gru were extracted using iterative pre-whitening and optimized using a multi-frequency non-linear least squares fit to the residual light curve (Bowman 2017). We provide the frequency list in Table 1. In total, 19 significant frequencies in the series of approximately equally-spaced frequencies were extracted. Although only the first 17 can be considered as 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 d^{-1} , follow the same pattern of being offset from an orbital harmonic. The frequency offset of each pulsation mode from a nearby orbital harmonic is also provided in Table 1, and significantly varies among the pulsation mode frequencies.

Furthermore, the amplitude spectrum of the residuals shown in Fig. 2 contains three additional independent pulsation mode frequencies that cannot be associated

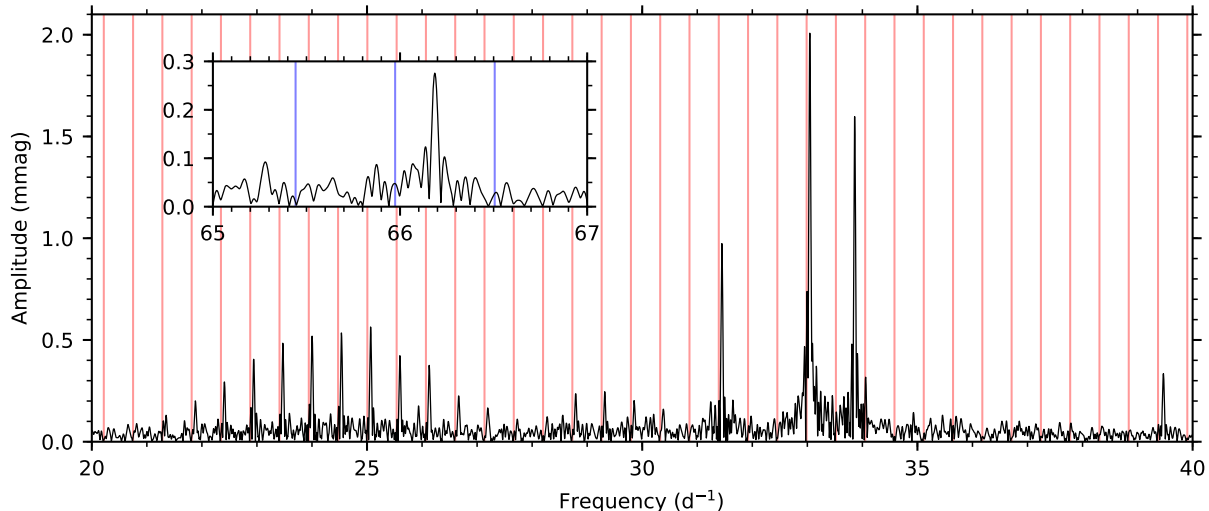


Figure 2. The residual amplitude spectrum after pre-whitening the orbital harmonics (denoted as vertical red lines in main panel and blue lines in sub-panel for clarity) in the TESS light curve of U Gru revealing independent pulsation mode frequencies.

with the series of frequencies offset from the orbital harmonics, and likely 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, yet many of them are related to the orbital frequency of the binary system.

3. DISCUSSION

The approximately equally-spaced series of pulsation modes in U Gru spans more than 17 frequencies, which are not exactly separated by the orbital frequency, nor is there a constant offset between each pulsation mode and the neighbouring harmonic of the orbital frequency. The frequency spacing within the series is too small to be the large frequency separation – i.e. the difference in frequency of consecutive radial order modes of the same angular degree – or the small frequency separation for either component considering the spectral types and the likely inferred parameters of the two stars (Brancewicz & Dworak 1980; Aerts et al. 2010).

We note that the highest amplitude pulsation mode in the residual amplitude spectrum (33.0442 d^{-1} ; Fig. 2) is not a sinc function as expected for periodic variability, and is exhibiting amplitude and/or frequency modulation (see e.g. Bowman et al. 2016). We demonstrate this in Fig. 3, in which the amplitude spectra of the first and last halves of the residual TESS light curve, i.e. after the binary signature has been removed, are over-plotted. Many of the pulsation modes in U Gru exhibit amplitude modulation on a timescale longer than the orbital period of the system, hence the total visible pulsation energy budget is changing over time.

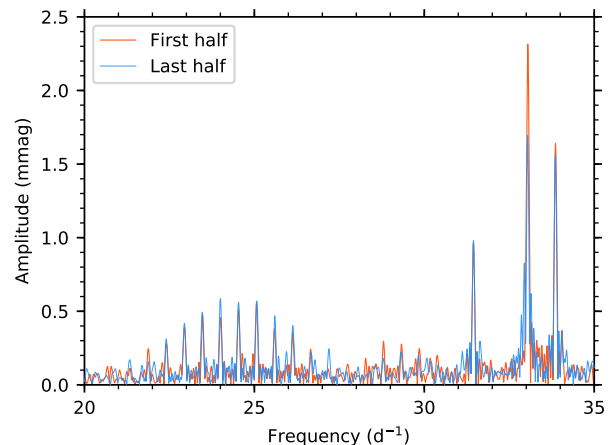


Figure 3. Overplotted amplitude spectra of the two halves of the residual TESS light curve of U Gru demonstrates significant amplitude modulation in many pulsation modes on a timescale longer than the orbital period.

We analysed the TESS light curve of U Gru with the PHOEBE eclipsing binary modeling code³ (Prša & Zwitter 2005; Prša et al. 2016) using a semi-detached configuration in which the secondary fills its Roche lobe and an assumption of zero eccentricity. Binary modeling and the totality of the primary eclipses confirms a near edge-on inclination, and indicates probable photometric mass ratio of order $q \simeq 0.17$, although the latter is unconstrained without spectroscopy. These preliminary results support the literature classification of U Gru being

³ <http://phoebe-project.org/>

Table 1. Frequencies, amplitudes and phases of the significant pulsation modes in U Gru. 1σ uncertainties calculated from the 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 harmonic of the orbital frequency, $n\nu_{\text{orb}}$, is also provided in the last column.

Frequency (d^{-1})	Amplitude (mmag)	Phase (rad)	S/N	$\nu - n\nu_{\text{orb}}$ (d^{-1})
21.8802 ± 0.0029	0.217 ± 0.032	0.46 ± 0.15	4.27	0.0775
22.4077 ± 0.0021	0.296 ± 0.032	-2.88 ± 0.11	4.92	0.0732
22.9411 ± 0.0015	0.413 ± 0.032	0.15 ± 0.08	6.03	0.0748
23.4696 ± 0.0013	0.490 ± 0.032	-3.13 ± 0.07	6.26	0.0716
24.0022 ± 0.0012	0.520 ± 0.032	-0.03 ± 0.06	6.37	0.0724
24.5349 ± 0.0012	0.545 ± 0.032	2.95 ± 0.06	6.37	0.0733
25.0644 ± 0.0011	0.564 ± 0.032	-0.41 ± 0.06	6.75	0.0710
25.5979 ± 0.0015	0.417 ± 0.032	2.59 ± 0.08	5.72	0.0728
26.1303 ± 0.0016	0.381 ± 0.032	-0.69 ± 0.08	5.70	0.0734
26.6644 ± 0.0028	0.225 ± 0.032	2.26 ± 0.14	4.33	0.0757
27.1966 ± 0.0040	0.155 ± 0.032	-1.37 ± 0.21	3.51	0.0762
27.7289 ± 0.0057	0.109 ± 0.032	0.30 ± 0.30	2.72	0.0767
28.2758 ± 0.0061	0.103 ± 0.032	-2.95 ± 0.32	2.44	0.0918
28.7910 ± 0.0025	0.246 ± 0.032	-0.78 ± 0.13	3.97	0.0752
29.3180 ± 0.0025	0.247 ± 0.032	2.16 ± 0.13	4.12	0.0705
29.8512 ± 0.0035	0.181 ± 0.032	-1.34 ± 0.18	3.12	0.0718
30.3800 ± 0.0037	0.167 ± 0.032	1.69 ± 0.19	2.77	0.0689
31.4469 ± 0.0006	0.984 ± 0.032	1.01 ± 0.03	8.17	0.0722
33.0442 ± 0.0003	1.997 ± 0.032	-2.16 ± 0.02	8.22	0.0743
33.8598 ± 0.0004	1.571 ± 0.032	0.95 ± 0.02	8.78	–
39.4689 ± 0.0020	0.323 ± 0.032	2.24 ± 0.10	6.72	–
66.1853 ± 0.0023	0.276 ± 0.032	0.41 ± 0.12	5.97	–

an Algol-like system (Brancewicz & Dworak 1980). 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 Fig. 4.

Synchronicity and circularisation are typically assumed for post-mass transfer systems (see Ogilvie 2014), 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. The pulsation modes frequencies in U Gru are significantly different and yet close to harmonics of the orbital frequency, which indicates that the influence of tides in this system is clearly important. MacLeod et al. (2018) recently investigated the scenario of tides in asynchronous binaries at the Roche limit using hydrodynamical simulations. The re-

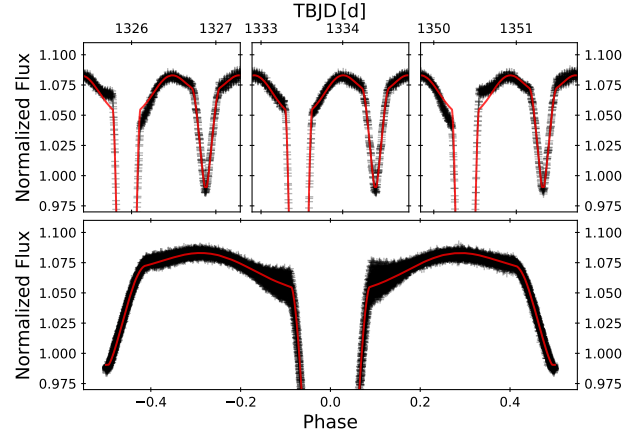


Figure 4. The binary model of U Gru (solid red line) overplotted on the phase-folded TESS observations (black points) is shown in the bottom panel. In the top row, the three panels show the same binary model for three different sections of the TESS light curve demonstrating the changes to shape of the light curve at ingress and egress in the primary eclipse, which produces the large envelope of pulsation scatter in the phase-folded light curve in the bottom panel.

sultant tidal forcing frequency, which is determined by the difference between the orbital and envelope rotation frequencies, passes through p-mode 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. 2018). However, such an evolution-based phenomenon is unlikely to be detected in a short light curve spanning only 28 d.

Possible explanations that could be responsible for the rich pulsation spectrum observed in U Gru are:

(i) *tidally-excited modes*: the tide generating potential of the U Gru system could excite a series of $\ell = 2$ modes, in which the particular range in radial order (n) provides information on the distorted pulsation cavity (Ogilvie 2014).

(ii) *tidally-perturbed modes*: the observed frequencies could be free oscillations that are self-excited by the opacity mechanism, but whose Eigenfrequencies are perturbed because of the tidal deformation of the pulsation cavity (Polfiet & Smeyers 1990; Reyniers 2002; Reyniers & Smeyers 2003a,b).

Since the eccentricity is close to, if not exactly, zero in U Gru, it is plausible that asynchronous rotation may be, in part, also responsible for the detected pulsation modes in U Gru. Of course, in a circular system with asynchronous components, each star is subject to a tidal torque. The case for asynchronous rotation in U Gru 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 modelling including spectroscopic radial velocities.

In any case, U Gru offers unique and exciting prospects for the application of tidal asteroseismology, as the influence of tides can be directly measured from the perturbations to observed pulsation mode frequencies. We are currently gathering the necessary high-resolution spectroscopy to 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 of the aforementioned scenarios (Johnston et al., *in prep*). 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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