High-Amplitude $\gamma$ Doradus Variables

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ABSTRACT

According to most literature sources, the amplitude of the pulsational variability observed in $\gamma$ Doradus stars does not exceed 0.1 mag in Johnson V. We have analyzed fifteen high-amplitude $\gamma$ Doradus stars with photometric peak-to-peak amplitudes well beyond this limit, with the aim of unraveling the mechanisms behind the observed high amplitudes and investigating whether these objects are in any way physically distinct from their low-amplitude counterparts. We have calculated astrophysical parameters and investigated the location of the high-amplitude $\gamma$ Doradus stars and a control sample of fifteen low-amplitude objects in the log $T_{\text{eff}}$ versus log $L/L_\odot$ diagram. Employing survey data and our own observations, we analyzed the photometric variability of our target stars using discrete Fourier transform. Correlations between the observed primary frequencies, amplitudes and other parameters like effective temperature and luminosity were investigated. The unusually high amplitudes of the high-amplitude $\gamma$ Doradus stars can be explained by the superposition of several base frequencies in interaction with their combination and overtone frequencies. Although the maximum amplitude of the primary frequencies does not exceed an amplitude of 0.1 mag, total light variability amplitudes of over 0.3 mag ($V$) can be attained in this way. Low- and high-amplitude $\gamma$ Doradus stars do not appear to be physically distinct in any other respect than their total variability amplitudes but merely represent two ends of the same, uniform group of variables.

Key words: stars: oscillations – stars: variables: general

1 INTRODUCTION

The $\gamma$ Doradus and $\delta$ Scuti stars are pulsating variables that are situated in the region of the A and F-type main sequence stars. For convenience, they are referred to hereafter as, respectively, GDOR and DSCT stars, according to their designations in the General Catalogue of Variable Stars (GCVS; Samus et al. 2009). In contrast to the long-known and very well studied DSCT stars (Fath 1935; Breger 2000), the variability of GDOR stars was discovered relatively recently. They were identified as a new class of variables by Balona et al. (1994) and defined as such by Kaye et al. (1999). The GDOR stars are characterized by high-order, low-degree, non-radial gravity (g) mode pulsation (Kaye et al. 1999), which is thought to be driven by the convective flux blocking mechanism (Guzik et al. 2000; Dupret et al. 2005). They are encountered between spectral types A7 and F7 (GCVS), although other sources have shifted the red border of the GDOR instability strip to somewhat hotter temperatures. Balona et al. (2011), for instance, find most GDOR stars in the effective temperature range from $6500 < T_{\text{eff}} < 7000$ K, corresponding to spectral types F1 to F5 on the main sequence, while Bradley et al. (2015) find all of their GDOR candidates between $6100 < T_{\text{eff}} < 7500$ K. However, it has been shown that there are also hot GDOR stars, which are located between the red edge of the Slowly Pulsating B star and the blue edge of the GDOR star instability strips (Balona et al. 2016; Kahraman Aliçavuş et al. 2020).

GDOR and DSCT stars can be distinguished by the timescales of the observed variability, although the instability strips for both classes overlap and hybrid-types exist (e.g. Henry & Fekel 2005). Several different classification systems are found in the literature. According to the GCVS, GDOR stars exhibit variability in the period range of $0.3 \leq P \leq 3 \text{ d}$ ($0.33 \leq f \leq 3.33 \text{ d}^{-1}$) (cf. Kaye et al. 1999), while DSCT stars are encountered in the period range of $0.01 \leq P \leq 0.2 \text{ d}$ ($5 \leq f \leq 100 \text{ d}^{-1}$). Based on an analysis of high-precision Kepler photometry, Grigahcène et al. (2010) proposed a division into ‘pure’ DSCT stars ($f > 5 \text{ c/d}$), ‘pure’ GDOR stars

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(f < 5 c/d), and hybrid-types exhibiting variability in both frequency regimes. While hybrid-type pulsators are mostly discovered in ultra-precise space photometry, their frequency of occurrence (∼25% of the sample of Uytterhoeven et al. 2011) has made clear that the situation is complex and the traditional classification scheme might be in need of revision. The understanding and relationship of DSCT and GDOR pulsators is currently in flux (e.g. Grigahcène et al. 2010; Uytterhoeven et al. 2011; Balona et al. 2011; Balona 2012; Balona 2018; Antoci et al. 2019).

Using Kepler data, Balona et al. (2011) described three groups of distinct GDOR star light curves. Two of these groups show pronounced beating effects. These are the SYM stars, which show more or less symmetric light curves, and the ASYM stars, whose light curves are asymmetric in the sense that the beat amplitude is larger when the star is brighter, which results in large variations in maximum brightness but only small variations in minimum brightness. The third group is made up of the MULT stars, which are characterized by many low-amplitude peaks that do not lead to pronounced beating in the light curve.

Kaye et al. (1999) indicate a photometric peak-to-peak amplitude of up to 0.1 mag in Johnson V for GDOR variables. This limit has been widely accepted and is found throughout the literature and variability catalogues, like e.g. the International Variable Star Index of the AAVSO (VSX; Watson 2006). The GCVS somewhat softens this statement, indicating that peak-to-peak amplitudes are usually up to 0.1 mag. In fact, at the time of this writing (March 2020), only 24 out of the 924 GDOR variables contained in the VSX are listed with amplitudes exceeding 0.1 mag, and the knowledge on these objects is limited.

This paper presents a detailed investigation of fifteen high-amplitude ($V_{\text{amp}} > 0.1$ mag) GDOR (referred to hereafter for convenience as HAGDOR = High-Amplitude Gamma DORadus) stars with survey data and our own observations, with the aim of unraveling the mechanisms behind the observed high amplitudes and investigating possible systematic differences between the group of the regular ($V_{\text{amp}} \leq 0.1$ mag) GDOR stars and the HAGDORs.

2 TARGET STARS AND ASTROPHYSICAL PARAMETERS

2.1 Target selection

The VSX was chosen as first source for selecting our initial sample stars as it is the most current and accurate variable star database available. At the time of this writing, it listed a total of 24 GDOR stars out of 924 stars with amplitudes exceeding 0.1 mag – including KIC 8113425, which was analyzed in detail by Kurtz et al. (2015). Ten of these objects boasted suitable photometric time series data allowing further detailed analyses and were hence selected for our sample. The stars KIC 7448050, KIC 6953103 and KIC 7304385, erroneously listed in the VSX with amplitudes less than 0.1 mag, were subsequently identified as HAGDOR stars and also included into our sample. As these examples illustrate, we suspect that, on detailed analysis, more low-amplitude GDOR stars listed in the VSX will likely turn out to be HAGDOR stars. Amplitude determination in these objects, which often show pronounced beating effects in their light curves, is not easy and prone to errors. An investigation into this matter, however, is beyond the scope of this paper. Finally, two more HAGDORs (HD 33575 and HD 211394) were identified in a systematic search among unclassified variables of suitable spectral type in the VSX. Both objects exhibit very large peak-to-peak amplitudes of more than 0.3 mag (V). In total, our final HAGDOR sample consists of 15 stars showing light change amplitudes in excess of 0.1 mag (V). Table 1 provides essential data for these objects.

For the six HAGDOR stars having both broadband Kepler ($K_p$) data and V-band data from the All-Sky Automated Survey for Supernovae (ASAS-SN; cf. Section 3), we calculated and compared semi-amplitudes in the different passbands and found that $\text{Amp}(V)/\text{Amp}(K_p) = 1.08(5)$. Assuming a colour-amplitude ratio of ~1.25 for GDOR stars (Handler & Shobbrook 2002) and employing the relations for the calibration of $K_p$ magnitudes given by Brown et al. (2011), we estimate $\text{Amp}(V)/\text{Amp}(K_p) = 1.065(20)$, in line with the above mentioned result. We have therefore adopted $\text{Amp}(V)/\text{Amp}(K_p) = 1.07(3)$ for the purposes of the present study.

Reduced peak-to-peak amplitudes in Kepler data are expected, as photometric pulsation amplitudes in early-type stars generally decrease with increasing wavelength, and the Kepler passband covers the wavelength range from 420-900 nm, with peak transmission at around 600 nm (cf. Section 3.3). As only one sample star boasts TESS data (HD 17721), a similar estimation of the relationship between $\text{Amp}(V)$ and $\text{Amp}(\text{TESS})$ was not possible. However, we expect that pulsation amplitudes will be even more reduced in the redder TESS passband (600-1000 nm; cf. Section 3.4). This is in line with the results of Antoci et al. (2019), who investigated DSCT and GDOR stars with TESS data and estimated that pulsation amplitudes derived from TESS data only reach 74(1) % of those derived from Kepler data. Using $\text{Amp}(V)/\text{Amp}(K_p) = 1.07$, we estimate $\text{Amp}(V)/\text{Amp}(\text{TESS}) = 1.44(4)$. The response functions of the Johnson V, Kepler and TESS passbands are shown in Fig. 1.

To investigate systematic differences between the groups of HAGDOR and GDOR variables, a control sample of regular GDOR stars was selected from the VSX using the following criteria: (a) light change amplitudes of 0.05 ≤ $V$ ≤ 0.1 mag, (b) the availability

Figure 1. Response functions of the Johnson V, Kepler and TESS passbands. Data have been gleaned from Johnson & Morgan (1951), Ricker et al. (2014) and the Kepler Instrument Handbook (https://keplerscience.arc.nasa.gov/).
of high-precision photometric time series data of suitable length that allow an in-depth analysis, (c) the availability of reliable astrophysical parameters, and (d) similar effective temperatures to the HAGDOR stars. The lower amplitude limit (1) was chosen because of the limitations of the employed ground-based photometric time series data (cf. also Section 3). Most GDOR stars in VSX have listed amplitudes that fail to satisfy criterion (1); therefore only 20 stars were selected. The stars of the regular GDOR sample can be gleaned from the lower part of Table 2.

2.2 Astrophysical parameters

Gaia DR2 (Gaia Collaboration et al. 2016, 2018; Arenou et al. 2018) includes effective temperatures, luminosities, and reddening values for nearly all our sample stars. As a first step, we checked the reliability of these parameters.

Effective temperatures were gleaned from the literature (Ammons et al. 2006; McDonald et al. 2012; Pinsonneault et al. 2012; Huber et al. 2014; Munari et al. 2014; De Cat et al. 2015; Frasca et al. 2016; Kunder et al. 2017), and mean values and standard errors were calculated. Unfortunately, for one HAGDOR star (GSC02831-00348), no parameters are available in the above-listed references. Reddening values were interpolated using the maps published by Green et al. (2018). Distances and their errors were derived from Gaia DR2 parallax data. Almost all our sample stars are located within 1 kpc from the Sun. Therefore, reddening is small but not negligible (A_V < 0.2 mag). The only exception is the GDOR star GSC 04281-00186, which is located in the Galactic disk (l = −0.45°).

To calculate luminosities of our sample stars, bolometric corrections (B.C.) and relative magnitudes V were needed. B.C. values are at a minimum for F-type stars (Pecaut & Mamajek 2013) and do not significantly influence the luminosity calculation. Unfortunately, no homogeneous source of V magnitudes is available for all our target stars. Therefore, mean values of the magnitudes published by Kharchenko (2001) and Henden et al. (2016) were calculated and G magnitudes from Gaia DR2 were transformed. The final mean astrophysical parameters are listed in Table 2.

Figure 2 shows a comparison between the values derived in this paper and the values derived from Gaia DR2. It becomes obvious that the Gaia reddening values are significantly larger than those derived from the reddening maps (upper panel). As a consequence, the corresponding luminosities are lower than the luminosities calibrated with the parallax data and the other observables (lower panel). The situation for the effective temperatures (middle panel) is different. With only three exceptions, all stars are located on the unity line within the errors. For each of the three outliers, only one effective temperature value is available in the literature. Therefore, it is not possible to investigate the reason for, and estimate the significance of, the outliers that are mentioned in the diagrams. In consequence, for the following analyses, we have used our own luminosity values and effective temperatures from Gaia DR2 because the latter have been derived in a homogeneous way.

Figure 3 presents the log T_eff versus log L/L⊙ diagram of our sample stars. Also shown are the GDOR (Dupret et al. 2004) instability strip and the red border of the DSCT (Breger & Pamyatnykh 1998) instability strip. No obvious differences are seen between the location of the GDOR and HAGDOR stars; both groups are well distributed over the whole main sequence up to log L/L⊙ < 1.1. Interestingly, most stars are also located in the DSCT instability strip but do not show any corresponding pulsations with a detectable amplitude in the here employed photometric time series data.

![Figure 2](image1.png)

**Figure 2**. Comparison of the reddening (upper panel), effective temperature (middle panel), and luminosity (lower panel) values derived in this paper (ordinate values; Table 2) and from GAIA DR2 (abscissa values). Filled and open circles denote HAGDOR and GDOR stars, respectively. Also indicated are the unity lines.

![Figure 3](image2.png)

**Figure 3**. The log T_eff versus log L/L⊙ diagram of our programme stars (Table 2). The red border of the DSCT (solid line), and the GDOR (dotted lines) instability strips are taken from Breger & Pamyatnykh (1998) and Dupret et al. (2004), respectively. The zero-age main sequence (dashed line) is taken from Claret (1995). Filled and open circles denote HAGDOR stars and GDOR stars, respectively.
Two objects deserve mention, which are situated well outside the instability strips. These are the GDOR stars GSC04281-00186 and GSC09289-02186. According to its calibrated astrophysical parameters, GSC09289-02186 is a G0 V star. GSC04281-00186 is apparently a G-type giant situated in a significantly reddened ($A_V = 1.4 \text{ mag}$) region at a Galactic latitude of $b \approx 0^\circ$. Nevertheless, even when neglecting reddening, we find the star still far above the terminal-age main sequence. Using the standard reddening correlation $A(V) = 3.45A(J) = 5.89A(H) = 7.69A(K_S)$ (Paunzen et al. 2017), the derived indices $(J - H)_0 = -0.115 \text{ mag}$ and $(H - K)_0 = 0.040 \text{ mag}$ are typical for an early B-type star (Straižys & Lazauskaite 2009). However, Gaia DR2 colours (and all others in the optical region) are typical for a G-type object. Also, the derived effective temperature from Gaia DR2 is in agreement with all other published values. The star’s status as an evolved object, therefore, seems to be beyond doubt. This is intriguing as giant stars are not expected to exhibit GDOR pulsation. Both objects are further discussed in Section 4.3.3.

### Table 1. Essential data for the sample HAGDOR stars, listed in order of increasing right ascension. The columns denote: (1) conventional identifier; (2) alternative identification; (3) right ascension (J2000); (4) declination (J2000); (5) peak-to-peak amplitude; the corresponding data source is provided in parentheses (A=ASAS-SN/A3=ASAS-3/K=Kepler/R=ROAD/T=TESS); (6) main period (d); (7) most recent spectral type from the literature. Positional information was taken from Data Release 2 (DR2) of the Gaia satellite mission (Gaia Collaboration et al. 2016, 2018; Arenou et al. 2018). Information on the relationship of the amplitudes in the different passbands can be gleaned from Section 2.1.

| (1) Object | (2) Alt. ID | (3) RA(J2000) | (4) Dec.(J2000) | (5) Amp. (Source) | (6) Main per. (d) | (7) Spec. Type (lit) |
|-----------|-------------|--------------|----------------|------------------|------------------|-------------------|
| GSC02831-00348 | V0758 And | 02 22.20.49 | +37 59 05.107 | 0.19 (A) | 0.924655 | n/a |
| HD 17721 | HIP 13089 | 02 48.15.087 | −57 39 42.498 | 0.14 (A3), 0.144 (T) | 1.087858 | A9 V (Houk & Cowley 1975) |
| HD 33757 | NSV 158 | 05 01 21.600 | −23 13 01.950 | 0.35 (A3), 0.35 (A) | 1.293260 | A9 V (Houk & Smith-Moore 1988) |
| HD 50875 | NSV 3272 | 06 34 33.947 | −11 23 29.468 | 0.22 (A3) | 1.705329 | F2 V (Wright et al. 2003) |
| HD 58693 | NSV 18291 | 09 52 56.364 | −26 45 20.219 | 0.17 (A3) | 1.125952 | F0 V (Houk 1982) |
| GSC09046-00646 | ASAS J163451-6446.3 | 16 34 50.969 | −64 46 18.299 | 0.21 (A3), 0.19 (A) | 1.180647 | n/a |
| HD 190538 | NSV 20738 | 16 41 29.100 | +06 16 33.387 | 0.21 (A3) | 1.386903 | F5 (Ochsenbein 1980) |
| KIC3847822 | TYC3134-2121-1 | 19 22 57.126 | +38 58 18.167 | 0.16 (A), 0.169 (K) | 1.204964 | n/a |
| KIC3441448 | GSC02780-00348 | V0758 And | 02 22.20.49 | +37 59 05.107 | 0.19 (A) | 0.924655 | n/a |
| KIC7440850 | ASAS J195052 | 19 23 21.727 | +38 32 58.614 | 0.10 (A), 0.122 (K) | 0.810700 | F0 V (Gray et al. 2016) |
| KIC6953103 | 2MASS J19325124 | 19 31 03.390 | +43 02 06.368 | 0.19 (A), 0.182 (K) | 0.877616 | A9 IV-V (Gray et al. 2016) |
| KIC8113425 | 2MASS J19474808 | 19 47 48.082 | +43 54 25.727 | 0.14 (A), 0.164 (K) | 2.325268 | F0 V (Frasca et al. 2016) |
| KIC7304838 | ASAS J195052+4248 | 19 50 51.541 | +42 48 06.015 | 0.14 (A), 0.146 (K) | 0.787874 | F5 (Skiff 2014) |
| HD 211394 | BD-17 6481 | 22 16 57.007 | −16 59 03.156 | 0.32 (A3), 0.29 (R), 0.324 (K) | 2.210397 | F0 V (Bouquillon et al. 2014) |
| GSC02780-02174 | TYC2780-2174-1 | 23 51 25.338 | +37 10 27.924 | 0.13 (A) | 0.943619 | F0 V (this work) |

Table 1. Essential data for the sample HAGDOR stars, listed in order of increasing right ascension. The columns denote: (1) conventional identifier; (2) alternative identification; (3) right ascension (J2000); (4) declination (J2000); (5) peak-to-peak amplitude; the corresponding data source is provided in parentheses (A=ASAS-SN/A3=ASAS-3/K=Kepler/R=ROAD/T=TESS); (6) main period (d); (7) most recent spectral type from the literature. Positional information was taken from Data Release 2 (DR2) of the Gaia satellite mission (Gaia Collaboration et al. 2016, 2018; Arenou et al. 2018). Information on the relationship of the amplitudes in the different passbands can be gleaned from Section 2.1.

3.2 The ASAS-SN photometric archive

The ASAS-SN survey is monitoring the entire visible sky every night to a depth of $V \leq 17$ mag (Shappee et al. 2014; Kochanek et al. 2017). The available data span up to six years of observations. As of end-2017, ASAS-SN observations are procured at five stations, each consisting of four 14 cm aperture Nikon telephoto lenses. Observations consist of three dithered 90 s exposures made through $V$ (two stations) or $g$ (three stations) band filters. ASAS-SN saturates at 10 to 11 mag, where the exact limit depends on the camera and the image position (vignetting). However, a procedure inherited from the original ASAS survey is applied which corrects for saturation but increases the noise in the affected data sets (Jayasinghe et al. 2018).

3.3 The Kepler satellite photometric archive

The Kepler satellite was launched in March 2009, with the primary goal of detecting transiting exoplanets in the solar neighbourhood. The spacebased photometer has a 0.95 m aperture; the detectors consist of 21 modules each equipped with two 2200×1024 pixel CCDs. Kepler provides single passband (420-900 nm; Koch et al. 2010) light curves of micromagnitude precision, taken in long-cadence (29.5 min) and short-cadence (58.5 s) modes (Gilliland et al. 2010), and has discovered hundreds of planet candidates (Borucki et al. 2010). The long, uninterrupted, and high-precision time series photometry is ideally suited to the study of multiperiodic pulsating stars (Tkachenko et al. 2012).

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* Derived from analysis of a publicly available LAMOST DR4 spectrum (Zhao et al. 2012; Cui et al. 2012).
Table 2. Mean astrophysical parameters of our target stars. The upper part of the table contains the HAGDOR stars, the lower part the GDOR stars. The columns denote: (1) conventional identifier; (2) alternative identification; (3,4) absorption in V and G; (5) bolometric correction, (6) V magnitude and error; (7,8) logarithmic effective temperature and error estimate; (9,10) logarithmic luminosity and error estimate.

| Object | Alt. ID | $A_V$ (our) | $A_G$ (our) | B.C. (our) | V | log $T_{\text{eff}}$ (our) | log $T_{\text{eff}}$ (DR2) | log $L/L_\odot$ (our) | log $L/L_\odot$ (DR2) |
|--------|---------|------------|------------|-----------|---|-------------------|-------------------|-------------------|-------------------|
| GSC02831-00348 | V0758 And | 0.11 | 0.55(39) | +0.10 | 11.390(4) | 3.883(20) | 0.80(3) | 0.78(2) |
| HD 17721 | HIP 13089 | 0.00 | 0.56(35) | -0.01 | 8.591(8) | 3.852(5) | 3.855(8) | 0.78(2) | 0.77(1) |
| HD 33575 | NSW 1858 | 0.05 | 0.76(28) | -0.01 | 9.708(2) | 3.866 | 3.855(8) | 0.84(2) | 0.82(1) |
| HD 50875 | NSW 3272 | 0.08 | 0.69(28) | -0.01 | 8.521(2) | 3.853 | 3.852(9) | 0.87(2) | 0.83(1) |
| HD 59563 | NSW 18291 | 0.01 | 0.85(30) | -0.01 | 7.679(2) | 3.839(1) | 3.845(14) | 0.92(2) | 0.90(1) |
| GSC09046-00646 | ASAS1163451-6446.3 | 0.22 | 0.62(31) | -0.01 | 10.251(2) | 3.822 | 3.843(6) | 0.89(2) | 0.80(1) |
| HD 150538 | NSW 20738 | 0.22 | 1.08(29) | -0.02 | 7.93(2) | 3.830(28) | 3.839(13) | 0.102(2) | 0.93(1) |
| KIC3874822 | TYC3134-2121-1 | 0.14 | 0.63(19) | -0.01 | 11.866(1) | 3.850(1) | 3.861(16) | 0.76(2) | 0.72(1) |
| KIC344144 | GSC03134-00901 | 0.16 | 0.48(38) | -0.01 | 11.539(2) | 3.855(11) | 3.854(8) | 0.83(3) | 0.77(1) |
| KIC7448050 | ASAS1193103-4302.1 | 0.11 | 0.62(24) | -0.01 | 11.838(2) | 3.861(14) | 3.860(8) | 0.79(2) | 0.76(1) |
| KIC6953103 | 2MASSJ19325124+4228465 | 0.19 | 0.36(26) | -0.01 | 12.593(2) | 3.854(11) | 3.855(11) | 0.73(3) | 0.68(2) |
| KIC8113425 | 2MASSJ19474808+4354257 | 0.47 | 1.35(11) | -0.04 | 13.931(1) | 3.841(8) | 3.820(16) | 0.85(3) | 0.67(3) |
| KIC7304385 | ASAS11955052-4248.1 | 0.14 | 0.78(25) | -0.01 | 10.078(1) | 3.847(18) | 3.834(14) | 0.85(2) | 0.80(1) |
| HD 211319 | BD-17 6481 | 0.08 | 1.29(22) | -0.04 | 9.306(3) | 3.826(9) | 3.882(3) | 0.97(3) | 0.92(1) |
| GSC02780-02174 | TYC2780-2174-1 | 0.30 | 0.92(29) | -0.02 | 11.754(2) | 3.875 | 3.815(10) | 0.78(3) | 0.66(1) |

3.4 The TESS satellite photometric archive

The Transiting Exoplanet Survey Satellite (TESS) mission is a two-year all-sky survey aiming at the discovery of transiting exoplanets (Ricker et al. 2015). To this end, four MIT/Lincoln Lab CCDs with 4096x4096 pixels are employed (imaging area of 2048x2048 pixels; the remaining pixels are used as a frame-store to allow rapid shutterless readout). The cameras have an effective aperture size of 10 cm and are equipped with f/1.4 lenses, resulting in a field of view of 24° x 24° per camera. The TESS passband covers the wavelength range from about 600-1000 nm. Due to their high photometric precision, time sampling of 2 min and long intervals of uninterrupted observations, TESS data are well suited to astroseismology (Campante et al. 2016).

3.5 The Remote Observeratory Atacama Desert (ROAD)

New CCD photometric observations of one target (HD 211394) were acquired at the Remote Observeratory Atacama Desert (ROAD; Hambach 2012). All observations were acquired through an As trodon Photometric V filter with an Orion Optics, UK Optimized Dall Kirkham 406/6.8 telescope and a FLI 16803 CCD camera. The exposure time was 5 s; twilight sky-flat images were used for flatfield corrections. Reductions were performed with the MAXIM DL program2. For the determination of magnitudes, the LeslePhotometry program3 was employed.

3.6 Method of analysis

The data of our target stars were downloaded from the ASAS-3 website4, the ASAS-SN archive5 and, in the case of Kepler and TESS data, the Mikulski Archive for Space Telescopes (MAST)6. All light curves were inspected visually. Obscure outliers and data

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2 http://www.cyanogen.com
3 http://www.dppobservatory.net/
4 http://www.asastronomy.edu/asas/
5 https://asassn.sn.osu.edu/
6 https://archive.stsci.edu/access-mast-data
points with very large uncertainties were carefully removed. In the case of the ASAS-3 data, measurements with a quality flag of ‘D’ (= worst data, probably useless) were deleted.

The time of the ASAS-3 and ASAS-SN observations are provided in HJD-2450000. Kepler and TESS data, however, are formatted as BJD-2454833 and BJD-2457000, respectively. To facilitate analysis, Kepler and TESS data have been converted to HJD-2450000 to bring them in line with the ground-based data.7

The period analysis was done using the program package PERIOD04 (Lenz & Breger 2005), which employs discrete Fourier transform and allows least-squares fitting of multiple frequencies to the data. To extract all relevant frequencies, the data were searched for periodic signals and consecutively prewhitened with the most significant frequencies. As detection threshold, we adopted S/N ≥ 4 (Breger et al. 1993).

4 PRESENTATION AND DISCUSSION OF RESULTS

In this section, we present example results and discuss the light variability patterns of the HAGDOR variables on the basis of the HAGDOR star KIC 8113425, which has been extensively studied by Kurtz et al. (2015) and is here employed as a model case.

4.1 The HAGDOR star KIC 8113425 as a model case

In their investigation of the complex frequency spectra of GDOR, Slowly Pulsating B stars and Be stars, Kurtz et al. (2015) extensively studied the HAGDOR star KIC 8113425. It has therefore been employed as a model case for a general interpretation of the light variations of our sample HAGDOR stars which also include KIC 8113425. Kurtz et al. (2015) noted the complex, strongly non-linear light variations of this star, which shows a much larger range at maximum light than minimum light (type ASYM), and identified 43 frequencies with semi-amplitudes greater than 1 mmag that cluster in five frequency groups. All these 43 frequencies can be understood in terms of only four base frequencies (\(f_1\) = 0.430058 d\(^{-1}\), \(f_2\) = 0.450101 d\(^{-1}\), \(f_3\) = 0.461264 d\(^{-1}\) and \(f_4\) = 0.489414 d\(^{-1}\)) and their combination frequencies up to the order 2\(f\) (e.g. 2\(f_1\), \(f_2\) + \(f_3\) − \(f_4\)). To trace and investigate the results of Kurtz et al. (2015), simulated light curves were calculated based on the frequency and phase information provided by the aforementioned authors.

The full Kepler light curve of KIC 8113425 and a detailed view are shown in the top panels of Figure 4. The other panels of this figure illustrate the simulated light curves using

a) all 43 frequencies,

b) seven frequencies (four base frequencies and the three detected overtone frequencies 2\(f_1\), 2\(f_2\) and \(f_4\)),

c) four frequencies (the base frequencies), and

d) one frequency (\(f_1\), the frequency with the largest semi-amplitude, 0.01455 mag).

We have investigated the contribution of the corresponding frequencies to the total variability amplitude. The base frequency \(f_1\) with its peak-to-peak amplitude of 0.028 mag accounts for only \(\sim 21\%\) of the total amplitude (0.137 mag) of the observed light variations. The four base frequencies together add up to an amplitude of

![Figure 4](https://example.com/figure4.png)

Figure 4. The two top panels show the full Kepler light curve of KIC 8113425 and the light curve in the interval HJD 2455060-80. The other panels illustrate the simulated light curves using a) 43 frequencies, b) seven frequencies, c) four frequencies and d) one frequency, as described in Kurtz et al. (2015).

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7 In all cases, the calculation of the phase values provided in the presentation of results has been based on the time basis of HJD-2450000.
Table 3. Frequency solution for HD 211394.

|   | Freq.No. | Frequency | Amplitude | Phase | ID |
|---|---------|-----------|-----------|-------|----|
| F1 ASAS-3 | 0.452407 | 0.049 | 0.7275 | \( f_1 \) |
| F2 ASAS-3 | 0.371387 | 0.027 | 0.6153 | \( f_2 \) |
| F3 ASAS-3 | 0.904804 | 0.020 | 0.7111 | \( 2f_1 \) |
| F4 ASAS-3 | 0.823776 | 0.018 | 0.6548 | \( f_1 + f_2 \) |
| F5 ASAS-3 | 1.276179 | 0.014 | 0.6848 | \( f_2 + 2f_1 \) |
| F1 ROAD | 0.452625 | 0.051 | 0.0744 | \( f_1 \) |
| F2 ROAD | 0.370860 | 0.026 | 0.7140 | \( f_2 \) |
| F3 ROAD | 0.823041 | 0.020 | 0.4374 | \( f_1 + f_2 \) |
| F4 ROAD | 0.904372 | 0.018 | 0.1150 | \( 2f_1 \) |
| F1 Kepler | 0.452538 | 0.04193 | 0.8082 | \( f_1 \) |
| F2 Kepler | 0.372089 | 0.01975 | 0.7546 | \( f_2 \) |
| F3 Kepler | 0.905160 | 0.01774 | 0.2723 | \( 2f_1 \) |
| F4 Kepler | 0.824686 | 0.01274 | 0.4111 | \( f_1 + f_2 \) |
| F5 Kepler | 0.080533 | 0.01063 | 0.3164 | \( f_1 - f_2 \) |
| F6 Kepler | 1.005225 | 0.01502 | 0.3856 | \( f_3 \) |
| F7 Kepler | 0.533652 | 0.00904 | 0.2196 | \( 2f_1 - f_2 \) |
| F8 Kepler | 1.357718 | 0.00816 | 0.2313 | \( f_4 \) |

Table 4. Frequency solution for KIC 3441414.

|   | Freq.No. | Frequency | Amplitude | Phase | ID |
|---|---------|-----------|-----------|-------|----|
| F1 ASAS-3 | 1.233502 | 0.021 | 0.5729 | \( f_1 \) |
| F2 ASAS-3 | 1.107843 | 0.010 | 0.7617 | \( f_2 \) |
| F3 ASAS-3 | 1.321001 | 0.007 | 0.2928 | \( f_3 \) |
| F1 Kepler | 1.233479 | 0.01841 | 0.1633 | \( f_1 \) |
| F2 Kepler | 1.107875 | 0.01237 | 0.8904 | \( f_2 \) |
| F3 Kepler | 1.320999 | 0.00622 | 0.6805 | \( f_3 \) |
| F4 Kepler | 0.125600 | 0.00350 | 0.1636 | \( f_1 - f_2 \) |
| F5 Kepler | 2.341354 | 0.00230 | 0.3444 | \( f_1 + f_2 \) |
| F6 Kepler | 0.543345 | 0.00176 | 0.3657 | \( f_3 \) |
| F7 Kepler | 0.962388 | 0.00170 | 0.4148 | \( f_3 \) |
| F8 Kepler | 2.466995 | 0.00164 | 0.6123 | \( 2f_3 \) |
| F9 Kepler | 1.465986 | 0.00138 | 0.7528 | \( f_6 \) |
| F10 Kepler | 0.087513 | 0.00134 | 0.4919 | \( f_1 - f_3 \) |
| F11 Kepler | 1.179790 | 0.00130 | 0.4088 | \( f_7 \) |
| F12 Kepler | 0.213140 | 0.00120 | 0.6362 | \( f_3 - f_5 \) |
| F13 Kepler | 0.508685 | 0.00109 | 0.6989 | \( f_8 \) |
| F14 Kepler | 1.661927 | 0.00109 | 0.3922 | \( f_6 \) |
| F15 Kepler | 1.742302 | 0.00108 | 0.0020 | \( f_6 \) |
| F16 Kepler | 1.539081 | 0.00105 | 0.6474 | \( 2f_6 - f_5 \) |
| F17 Kepler | 0.034023 | 0.00102 | 0.4082 | \( -2f_1 + f_3 + f_7 \) |
| F18 Kepler | 1.652501 | 0.00095 | 0.9946 | \( f_1 - f_4 + f_6 \) |

4.2 Light variability pattern of the other HAGDOR variables

Eight stars of our sample boast satellite photometry from \( \textit{Kepler} \) or TESS that allow a similarly detailed analysis. For the remaining seven objects with only ground-based observations, however, the precision and number of available measurements is not sufficient to perform an analysis of a vast number of frequencies. Nevertheless, it becomes obvious that all of our sample HAGDOR stars exhibit multiperiodic variability in a similar way to KIC8113425: in all objects, the beating of closely spaced frequencies results in total amplitudes that considerably exceed the amplitudes of the base frequencies. This leads to the observed ‘upward trends’ in the light curves, as described in Kurtz et al. (2015) and clearly seen for example in the light curves of KIC8113425 (Fig. 4, upper panel), HD 211394 and KIC 3441414 (both Fig. 5). These upward trends can for example arise if the phase difference of the second harmonic in relation to the base frequency is nearly zero, as has been observed for \( f_1 \) in KIC8113425. Similar upward trends are clearly present in the light curves of all other investigated HAGDOR variables, although in ASAS-3 and ASAS-SN data, these are sometimes only represented by a ‘smattering’ of bright data points around the time of maximum light in the phase diagrams. All HAGDOR stars, therefore, belong to the ASYM group of Balona et al. (2011) (cf. also Section 4.3).

As examples, Fig. 5 illustrates the \( \textit{Kepler} \) light curves of the two HAGDOR stars HD 211394 and KIC 3441414. The large peak-to-peak amplitudes of the observed variations (0.324 and 0.122 mag, respectively) become directly obvious. HD 211394, in particular, is noteworthy because it is one of the stars with the largest amplitude in our sample. Using \( \text{Amp}(V)/\text{Amp}(Kp)=1.07(3) \) (cf. Sect. 2.1), its light variations reach a peak-to-peak amplitude in \( V \) of about 0.35 mag, which is only rivalled by the variability of HD 33575 (\( \text{Amp}(V)=0.35 \) mag).

The corresponding Fourier amplitude spectra are shown in Fig. 6, the frequency solutions, as derived from the different data sources, are presented in Tables 3 and 4. Fig. 6 also illustrates the higher noise level, lower sampling rate and the presence of one-day aliases peaks in the ground-based ASAS-3 and ASAS-SN data. Nevertheless, these data span a much longer time baseline and are still very much suitable for the goals of the present investigation, which is also demonstrated by the good agreement between the principal frequencies derived from the different data sources. We also note that pulsation amplitudes are higher in \( V \) than in the broad-band \( \textit{Kepler} \) and TESS data, which can also be seen in Fig. 6 (cf. Sect. 2.1).

The frequency solutions for all stars are shown in the Appendix in Section A. Fourier amplitude spectra of all HAGDOR stars are presented in Section B.

In summary, we conclude that the observed high amplitudes in the HAGDOR stars are caused by the presence of multiple, closely-spaced frequencies and their interactions. In this way, although the maximum amplitude of the primary frequencies does not exceed an amplitude of 0.1 mag, total light variability amplitudes of over 0.3 mag (\( V \)) can be attained, as for example in the case of HD 211394 and HD 33575. This is an interesting result that shows the need for the revision of the customary GDOR star class definition and provides important input for pulsational modeling attempts.
4.3 Comparison of the samples of GDOR and HAGDOR variables

Several studies have indicated that high-amplitude DSCT (HADS) stars are distinguished from the lower-amplitude DSCT variables by several criteria: they generally show only one or two excited radial modes (usually the fundamental mode and/or first harmonic) and are mostly slow rotators, which seems to be a requirement for the observed high-amplitude pulsation (Breger 2000; McNamara 2000). It has also been postulated that HADS stars are at an evolutionary stage that puts them between low-mass classical Cepheids and high-mass DSCT stars; however, in their investigation of the physical nature of HADS stars using Kepler data, Balona et al. (2016) rejected this scenario and found that HADS stars are distributed randomly across the DSCT instability strip. No physical attribute was found that separates HADS stars from their low-amplitude counterparts, although there seems to be a general tendency for the number of combination frequencies to increase with increasing amplitude of the parent frequencies (Balona et al. 2016). Further investigation into the relationship between DSCT, HADS stars and the related low-metallicity SX Phe stars is clearly desirable.

Here we investigate the relationship between HAGDOR and GDOR stars. Their locations in the instability strip (Fig. 3) and log $T_{\text{eff}}$ versus log $L/L_\odot$ diagram (cf. Section 2.2) suggest that GDOR and HAGDOR stars are not physically distinct objects but rather a homogeneous group of variables. To further tackle this question, we have investigated the relation between the primary variability frequency and the parameters effective temperature and luminosity (Fig. 7). Both GDOR and HAGDOR stars overlap in the investigated parameter spaces and no significant correlation was found. The situation is similar for the semi-amplitudes of the primary frequencies: although HAGDOR stars tend to show larger amplitudes, as expected, no distinct boundary between GDOR and HAGDOR stars is observed but rather a gradual transition and considerable overlap. We have also correlated the two most significant frequencies and their corresponding semi-amplitudes (Fig. 7, right panels). Again, while HAGDOR stars tend to show larger ampli-
GDOR realm, whose red border is found at a spectral type of approximately 5000 K in their sample of GDOR stars with multiple light modes (e.g. Kurtz et al. 2015) as a model case.

We found that all HAGDOR variables show light curves of the ASYM type and behave similarly to KIC 8113425 in that they exhibit multiple frequencies whose beating results in total amplitudes considerably exceeding the amplitudes of the base frequencies. Hence, the high amplitudes observed in the HAGDOR stars can be explained by the superposition of several base frequencies in interaction with their combination and overtone frequencies. Although the maximum amplitude of the primary frequencies does not exceed an amplitude of 0.1 mag, total light variability amplitudes of over 0.3 mag (V) can be attained in this way – important input for pulsational modeling attempts. We conclude that a revision of the traditional amplitude cut-off of 0.1 mag (V) for GDOR stars is necessary. Based on the analyses of the present investigation, we propose a new cut-off value of 0.35 mag (V). We caution, however, that this conclusion has been based on the analysis of a small sample and HAGDOR stars with larger amplitudes may be found subsequently.

To tackle the question whether HAGDOR stars and GDOR stars are physically distinct objects, correlations between the observed primary frequencies, amplitudes and other parameters like effective temperature and luminosity were investigated. HAGDOR stars tend to show larger amplitudes, and nearly all of the investigated stars exhibit closely-spaced primary frequencies, which seems to be a general characteristic of the class of GDOR variables.

We have investigated high-amplitude GDOR (HAGDOR) stars showing light variability amplitudes well beyond the traditional 0.1 mag (V) limit, with the aim of unraveling the mechanisms behind the observed high amplitudes and investigating whether these objects are in any way physically distinct from regular GDOR stars (V_{max} ≤ 0.1 mag). To this end, a sample of 15 HAGDOR stars and a control sample of 20 regular GDOR stars boasting extensive photometric time series data were collected.

As a first step, we calculated astrophysical parameters and investigated our sample stars in the log $T_{\text{eff}}$ versus log $L/L_\odot$ diagram. No significant differences between the location of the HAGDOR stars and the GDOR stars were found – both groups are well distributed over the whole main sequence up to log $L/L_\odot < 1.1$. Employing publicly available survey data (Kepler, ASAS-3, ASAS-SN and, in the case of one star, TESS data) and our own observations, we analyzed the photometric variability of our target stars, using the well-described HAGDOR star KIC 8113425 (Kurtz et al. 2015) as a model case.

We caution, however, that this conclusion has been based on the analysis of a small sample and HAGDOR stars with larger amplitudes may be found subsequently.

To tackle the question whether HAGDOR stars and GDOR stars are physically distinct objects, correlations between the observed primary frequencies, amplitudes and other parameters like effective temperature and luminosity were investigated. HAGDOR stars tend to show larger amplitudes, and nearly all of the investigated stars exhibit closely-spaced primary frequencies, which seems to be a general characteristic of the class of GDOR variables. Apart from that, however, no significant differences were found; instead, both groups overlap and show gradual transitions.
GSC 09289-02186 and GSC 04281-00186 are indicated, respectively, by an orange triangle and a blue rectangle in all plots. The panels investigate primary constituent the most obvious outliers in the investigated parameter frequencies of our sample stars. Furthermore, both stars are and GSC 04281-00186, which exhibit the highest principal pulsation frequencies (upper right) and their corresponding semi-amplitudes (lower right). There generally is no significant difference in distribution between HAGDOR and GDOR stars, which do not seem to be physically distinct in any other respect than their total variability amplitudes.

**Figure 7.** Correlations between several observables for the sample of HAGDOR stars (black circles) and GDOR stars (open diamonds). The GDOR stars GSC 09289-02186 and GSC 04281-00186 are indicated, respectively, by an orange triangle and a blue rectangle in all plots. The panels investigate primary frequency versus effective temperature (upper left), semi-amplitude of the primary frequency versus effective temperature (lower left), primary frequency versus luminosity (upper middle), semi-amplitude of the primary frequency versus luminosity (lower middle), the correlation between the two most significant frequencies (upper right) and their corresponding semi-amplitudes (lower right). There generally is no significant difference in distribution between HAGDOR and GDOR stars, which do not seem to be physically distinct in any other respect than their total variability amplitudes.

**Figure 8.** Fourier amplitude spectrum of the G-type giant pulsator GSC 04281-00186, based on unwhitened ASAS-SN data. The y-axis denotes semi-amplitudes, as derived with PERIOD04.

in the investigated parameter spaces. We therefore conclude that low- and high-amplitude GDOR stars are not physically distinct in any other respect than their total variability amplitudes but merely represent two ends of the same, uniform group of variables. However, we caution that the sample sizes used for our investigation are small (15 HAGDOR stars and a comparison sample of 20 regular GDOR stars with total variability amplitudes of $0.05 \leq V \leq 0.1$ mag); our conclusions, therefore, should be confirmed using a larger sample of stars with good photometric time series observations.

We call attention to the GDOR variables GSC 09289-02186 and GSC 04281-00186, which exhibit the highest principal pulsation frequencies of our sample stars. Furthermore, both stars are situated outside the traditional boundaries of the GDOR realm and constitute the most obvious outliers in the investigated parameter spaces. Although some discrepancies in the available data exist, according to its calibrated astrophysical parameters, GSC 04281-00186 is a G-type giant, which is intriguing as GDOR stars belong to luminosity classes IV or V by definition. Further detailed studies of these objects are encouraged.

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**DATA AVAILABILITY**

The data underlying this article will be shared on reasonable request to the corresponding author.

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**APPENDIX A: FREQUENCY SOLUTIONS**

In the following, the frequency solutions for all sample stars are presented in tabular form. Stars are listed in order of increasing right ascension. In each table, the columns denote: (1) frequency
number; (2) frequency value; (3) semi-amplitude; (4) corresponding phase; (5) frequency identification. All values have been derived using PERIOD04, as outlined in Section 3.6.
### Table A1. Frequency solution for GSC 02831-00348 (V0758 And).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq. No. | Frequency | Amplitude | Phase | ID |
| F1 | 1.081484 | 0.052 | 0.6574 | f1 |
| F2 | 1.155404 | 0.010 | 0.7579 | f2 |

### Table A2. Frequency solution for HD 17721 (HIP 13089).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq. No. | Frequency | Amplitude | Phase | ID |
| F1ASAS-SN | 0.919238 | 0.025 | 0.3389 | f1 |
| F2ASAS-SN | 1.065821 | 0.021 | 0.1973 | f2 |

### Table A3. Frequency solution for HD 33575 (NSV 1858).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq. No. | Frequency | Amplitude | Phase | ID |
| F1ASAS-SN | 0.846993 | 0.025 | 0.9727 | f1 |
| F2ASAS-SN | 0.560801 | 0.020 | 0.1025 | f2 |

### Table A4. Frequency solution for HD 50875 (NSV 3272).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq. No. | Frequency | Amplitude | Phase | ID |
| F1ASAS-SN | 0.919038 | 0.025 | 0.7579 | f1 |
| F2ASAS-SN | 0.915570 | 0.011 | 0.0795 | f2 |

### Table A5. Frequency solution for HD 85693 (NSV 18291).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq. No. | Frequency | Amplitude | Phase | ID |
| F1ASAS-SN | 0.888140 | 0.034 | 0.8495 | f1 |
| F2ASAS-SN | 0.778475 | 0.021 | 0.9916 | f2 |
| F3ASAS-SN | 1.666578 | 0.014 | 0.2639 | f1 + f2 |
| F4ASAS-SN | 0.793137 | 0.012 | 0.0540 | f3 |

### Table A6. Frequency solution for GSC 09046-00646 (ASAS J163451-6446.3).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq. No. | Frequency | Amplitude | Phase | ID |
| F1ASAS-SN | 0.560868 | 0.023 | 0.3169 | f1 |
| F2ASAS-SN | 0.847028 | 0.024 | 0.0205 | f2 |

### Table A7. Frequency solution for HD 150538 (NSV 20738).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq. No. | Frequency | Amplitude | Phase | ID |
| F1ASAS-SN | 0.721031 | 0.033 | 0.4240 | f1 |
| F2ASAS-SN | 1.140350 | 0.020 | 0.9765 | f2 |

### Table A8. Frequency solution for KIC 3847822 (TYC 3134-2121-1).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq. No. | Frequency | Amplitude | Phase | ID |
| F3Kepler | 0.829875 | 0.01600 | 0.6923 | f1 |
| F2Kepler | 0.963154 | 0.01494 | 0.7443 | f2 |
| F3Kepler | 0.915471 | 0.00771 | 0.8871 | f3 |
| F4Kepler | 1.096999 | 0.00762 | 0.9753 | f4 |
| F5Kepler | 0.133330 | 0.00673 | 0.5757 | f5 |
| F6Kepler | 0.085594 | 0.00347 | 0.0515 | f6 |
| F7Kepler | 0.047627 | 0.00345 | 0.1426 | f7 |
| F8Kepler | 0.267117 | 0.00339 | 0.1179 | f8 |
| F9Kepler | 0.133790 | 0.00420 | 0.3820 | f9 |

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Table A9. Frequency solution for KIC 3441414 (GSC 03134-00091).

| Freq.No.  | Frequency | Amplitude | Phase | ID |
|-----------|-----------|-----------|-------|----|
| F1ASAS-SN | 1.233502  | 0.021     | 0.5729| f1 |
| F2ASAS-SN | 1.107843  | 0.010     | 0.7617| f2 |
| F3ASAS-SN | 1.321001  | 0.007     | 0.2928| f3 |

Table A10. Frequency solution for KIC 7448050 (ASAS J193103+4302.1).

| Freq.No.  | Frequency | Amplitude | Phase | ID |
|-----------|-----------|-----------|-------|----|
| F1ASAS-SN | 1.139451  | 0.031     | 0.9378| f1 |
| F2ASAS-SN | 1.043578  | 0.014     | 0.3619| f2 |
| F3ASAS-SN | 1.560555  | 0.013     | 0.7565| f3 |
| F4ASAS-SN | 2.278806  | 0.006     | 0.8760| f4 |

Table A11. Frequency solution for KIC 6953103 (2MASS J19325124+4228465).

| Freq.No.  | Frequency | Amplitude | Phase | ID |
|-----------|-----------|-----------|-------|----|
| F1Kepler  | 1.287599  | 0.03357   | 0.7980| f1 |
| F2Kepler  | 1.1161789 | 0.02269   | 0.5773| f2 |
| F3Kepler  | 1.198750  | 0.02199   | 0.1149| f3 |

Table A12. Frequency solution for KIC 8113425 (2MASS J19474808+4354257).

| Freq.No.  | Frequency | Amplitude | Phase | ID |
|-----------|-----------|-----------|-------|----|
| F1Kepler  | 0.429956  | 0.014     | 0.7265| f1 |
| F2Kepler  | 0.489422  | 0.011     | 0.2704| f2 |
| F3Kepler  | 0.449965  | 0.008     | 0.2736| f3 |

MNRAS 000, 1–15 (2020)
Table A13. Frequency solution for KIC 7304385 (ASASJ195052+4248.1).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq.No. | Frequency | Amplitude | Phase | ID |
| F1 | 1.269238 | 0.02562 | 0.9781 | f1 |
| F2 | 1.418047 | 0.02075 | 0.1262 | f2 |
| F3 | 1.462331 | 0.00796 | 0.6361 | f3 |
| F4 | 0.148812 | 0.00671 | 0.0651 | f2 − f1 |
| F5 | 1.487632 | 0.00467 | 0.1299 | f4 |
| F6 | 2.687285 | 0.00408 | 0.4037 | f3 + f1 |
| F7 | 1.120411 | 0.00296 | 0.9132 | 2f1 − f2 |
| F8 | 1.243951 | 0.00301 | 0.9347 | f1 + f3 − f4 |
| F9 | 2.538475 | 0.00294 | 0.2640 | 2f1 |
| F10 | 0.635646 | 0.00242 | 0.1740 | f5 |
| F11 | 0.193106 | 0.00242 | 0.5330 | −f1 + f5 |
| F12 | 1.566863 | 0.00229 | 0.4698 | 2f2 − f1 |
| F13 | 1.076156 | 0.00234 | 0.8462 | 2f1 − f5 |
| F14 | 1.180661 | 0.00211 | 0.3085 | f1 − 2f2 + f5 |
| F15 | 0.152996 | 0.00184 | 0.8403 | −2f1 + f2 + 2f5 |
| F16 | 2.053669 | 0.00175 | 0.5396 | f2 + f3 |
| F17 | 1.116238 | 0.00152 | 0.9054 | f6 |
| F18 | 1.095130 | 0.00150 | 0.6154 | 2f2 |

Table A14. Frequency solution for HD 211394 (BD-17 6481).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq.No. | Frequency | Amplitude | Phase | ID |
| F1 | 0.452407 | 0.049 | 0.7275 | f1 |
| F2 | 0.371387 | 0.027 | 0.6153 | f2 |
| F3 | 0.904804 | 0.020 | 0.7111 | 2f1 |
| F4 | 0.823041 | 0.018 | 0.4374 | f1 + f2 |
| F5 | 1.276179 | 0.014 | 0.6848 | f2 + 2f1 |
| F1 | 0.452625 | 0.051 | 0.0744 | f1 |
| F2 | 0.370860 | 0.026 | 0.7140 | f2 |
| F3 | 0.823041 | 0.020 | 0.4374 | f1 + f2 |
| F4 | 0.904372 | 0.018 | 0.1150 | 2f1 |

Table A15. Frequency solution for GSC 02780-02174 (TYC 2780-2174-1).

| (1) | (2) | (3) | (4) | (5) |
|-----|-----|-----|-----|-----|
| Freq.No. | Frequency | Amplitude | Phase | ID |
| F1 | 1.059750 | 0.034 | 0.3190 | f1 |
| F2 | 1.245288 | 0.013 | 0.8264 | f2 |
| F3 | 1.476331 | 0.008 | 0.9466 | f3 |
| F4 | 1.114903 | 0.008 | 0.4843 | f4 |
APPENDIX B: FOURIER AMPLITUDE SPECTRA

This section provides the Fourier amplitude spectra of all HAG-DOR stars, based on unwhitened data. The y-axes denote semi-amplitudes, as derived with PERIOD04. The employed data source is indicated in the panels. More information on the period analysis is provided in Section 3.6.

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Figure B1. Fourier amplitude spectra for all HAGDOR stars, based on unwhitened data. The employed data source is indicated in the panels.
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