Spectroscopy of hot $\gamma$ Doradus and A-F hybrid $Kepler$ candidates close to the hot border of the $\delta$ Scuti instability strip

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ABSTRACT

If $\gamma$ Dor-type pulsations are driven by the convective blocking mechanism, a convective envelope at a sufficient depth is essential. There are several hot $\gamma$ Dor and hybrid star candidates in which there should not be an adequate convective envelope to excite the $\gamma$ Dor-type oscillations. The existence of these hot objects needs an explanation. Therefore, we selected, observed and studied 24 hot $\gamma$ Dor and hybrid candidates to investigate their properties. The atmospheric parameters, chemical abundances and $v \sin i$ values of the candidates were obtained using medium-resolution ($R = 46,000$) spectra taken with the FIES instrument mounted at the Nordic Optical Telescope. We also carried out frequency analyses of the $Kepler$ long- and short-cadence data to determine the exact pulsation contents. We found only five bona-fide hot $\gamma$ Dor and three bona-fide hot hybrid stars in our sample. The other 16 stars were found to be normal $\gamma$ Dor, $\delta$ Sct, or hybrid variables. No chemical peculiarity was detected in the spectra of the bona-fide hot $\gamma$ Dor and hybrid stars. We investigated the interplay between rotation and pulsational modes. We also found that the hot $\gamma$ Dor stars have higher $Gaia$ luminosities and larger radii compared to main-sequence A-F stars.

Key words: stars: general – stars: abundances – stars: atmospheres – stars: rotation – stars: variables: $\gamma$ Doradus

1 INTRODUCTION

The $Kepler$ spacecraft [Koch et al. 2010; Borucki et al. 2010] was originally launched to detect Earth-like transiting planets, but it also shed new light on many other aspects of stellar astrophysics (e.g. Pizzocaro, et al. 2014; Compton, Bedding & Stello 2019; Helminiak, et al. 2019). In particular, new discoveries about pulsating stars provided important input for asteroseismology, opening new frontiers and posing new questions. Some of those concern the classes of the A- and F-type pulsating variables located on or close to the main sequence, i.e., $\delta$ Scuti ($\delta$ Sct) and $\gamma$ Doradus ($\gamma$ Dor) stars.

The $\delta$ Sct stars generally exhibit pressure ($p$) modes which are excited by the $\kappa$ mechanism in the HeII ionization zone. They typically oscillate with frequencies higher than $\sim 5 \text{ d}^{-1}$. The $\delta$ Sct stars are mostly placed in the lower part of the classical instability strip. Recently, Murphy et al. (2019) classified a sample of over 15,000 $Kepler$ A-type and F-type targets into $\delta$ Sct and non-$\delta$ Sct stars, also providing a subdivision in groups on the basis of the observed pulsation properties. They also defined a new empirical instability strip for $\delta$ Sct stars.
The γ Dor stars are a little cooler than the δ Sct variables. The gravity (g) mode oscillations of γ Dor stars are believed to be excited by the convective blocking mechanism (Guzik et al. 2000) with frequencies typically lower than 5 d\(^{-1}\). In a recent study, it was suggested that the δ Dor-type pulsations are caused by the combination of κ mechanism and the convection-oscillation coupling (Xiong et al. 2016). The γ Dor domain partially overlaps the cool border of the theoretical instability strip of δ Sct stars. In this part, new variables called A-F type hybrid stars were predicted (Handler 1999; Dupret et al. 2004). These stars display both δ Sct and γ Dor type pulsations, i.e., p and g modes.

Before Kepler, only a few hybrid stars had been discovered by means of ground-based observations (Henry & Fekel 2001; Uytterhoeven et al. 2008; Handler 2009) and their positions in the Hertzsprung-Russell (H-R) diagram matched very well with the theoretically predicted region. The precision and near continuous nature of Kepler photometry revolutionized the field, showing that apparently there are many A-F type hybrid stars located beyond the theoretical region (Grigahcène et al. 2010; Uytterhoeven et al. 2011). On the other hand, it was also found that some δ Sct and γ Dor stars are also placed outside the respective instability strips. These results give rise to conflicts with theory. Therefore, it was timely to fix the exact positions of these variables in the H-R diagram and to revise the borders of their instability strips. For these reasons, spectroscopic studies were carried out to determine accurate atmospheric parameters of δ Sct, γ Dor, and hybrid stars (e.g. Tkachenko et al. 2012; Niemczura et al. 2013, 2017). These investigations confirmed that some stars are actually outside the theoretical instability strips.

In particular, Balona (2014) and Balona et al. (2016) noticed how some gravity-mode pulsators are located close to, and even beyond, the hot border of δ Sct instability strip, defining them as hot γ Dor stars. These variables are remarkable objects because if the theory of convective driving would apply to stars located in this part of the H-R diagram then they should not have a sufficient convective envelope to drive the γ Dor-type pulsations. It has been suggested that the hot γ Dor stars could be A- or B-type stars with a cooler γ Dor companion, or simply stars with wrong determinations of the effective temperature (\(T_{\text{eff}}\)). A spectroscopic study of hot γ Dor stars was undertaken (Balona et al. 2014) and it turned out that the resulting \(T_{\text{eff}}\) values were mostly consistent with those given in the Kepler input catalog (KIC; Brown et al. 2011). However, the binary nature of the stars was not assessed and also the chemical composition of these variables could not be probed due to the low resolution of the spectra.

Another explanation is that the hot γ Dor stars are actually rapidly-rotating slowly pulsating B (SPB) stars (Balona et al. 2016). Due to gravity darkening, their equatorial zones appear cooler than the rest of the surface, then they are classified as hot A-stars and, hence, as hot γ Dor variables. If this hypothesis is true, all hot γ Dor stars should rotate with high rotational velocities. There are also some hot hybrid stars which are located in the same area of the H-R diagram. In both cases the γ Dor-type pulsation conflicts with the theory, since would require that the convective blocking mechanism is continuing to be active in the hottest A stars (Balona 2014). The g mode pulsation in those

![Figure 1. The positions of the selected candidate γ Dor (star symbols) and hybrid (diamonds) stars. The parameters of the stars were taken from Huber et al. (2014). The theoretical instability strips of the γ Dor (dashed lines) and δ Sct (solid lines) stars were taken from Dupret et al. (2003). The evolutionary tracks (Z = 0.02) were adopted from Kahraman Aliçavuş et al. (2016). γ Dor stars can also be explained by the radiative κ mechanism and the coupling between oscillation and convection (Xiong et al. 2016).](image-url)

\[\text{Figure 1. The positions of the selected candidate γ Dor (star symbols) and hybrid (diamonds) stars. The parameters of the stars were taken from Huber et al. (2014). The theoretical instability strips of the γ Dor (dashed lines) and δ Sct (solid lines) stars were taken from Dupret et al. (2003). The evolutionary tracks (Z = 0.02) were adopted from Kahraman Aliçavuş et al. (2016). γ Dor stars can also be explained by the radiative κ mechanism and the coupling between oscillation and convection (Xiong et al. 2016).}\]

In this study, a new spectroscopic survey of a selected sample of hot γ Dor and hybrid stars is presented. We focused on the candidate γ Dor and hybrid stars located close to the hot border of the δ Sct instability strip. We aim to answer the following questions. First, are the \(T_{\text{eff}}\) values of these hot objects correct? Second, do the hot γ Dor stars have hotter A- or B-type companions? Third, are the hybrid stars members of binary or multiple systems? Can those hot variables be rapidly-rotating stars? Additionally, are hot γ Dor and hybrid stars chemically peculiar? Therefore, we present a detailed spectroscopic analysis to determine the atmospheric parameters (\(T_{\text{eff}}\) surface gravity \(\log g\), and microturbulence velocity \(\xi\)), projected rotational velocities, binarity effects, and surface chemical abundances.

The target selection is described in Sect. 2. The spectroscopic observations, data reduction and normalisation in Sect. 3. The determinations of the atmospheric parameters from photometric indices, spectral energy distribution (SED), the analysis of Balmer and metal lines are discussed in Sect. 4. The chemical abundance analysis is presented in Sect. 5. The frequency analysis of the targets is performed in Sect. 6. The discussion and conclusions are given in Sects. 7 and 8 respectively.

### 2 TARGET SELECTION

We started the selection process from the γ Dor and hybrid star candidates listed in the study of Uytterhoeven et al. (2011). They were proposed on the basis of their Kepler light curves and preliminary atmospheric parameters listed in the KIC. To better characterize them, we used the improved parameters reported in the revised Kepler catalog of Huber et al. (2014, hereafter H14), the latest available at the time of our observations (October 2016). This catalog is based on a compilation of literature values for at-
mospheric properties derived from a variety of observational techniques.

High-resolution spectroscopy of a well-constrained sample of stars should provide reliable answers to the questions posed in Sect. 4 especially when combining this technique with a homogeneous reduction and analysis of the spectra taken with a single instrument.

To refine our selection, we considered that the γ Dor stars have \( T_{\text{eff}} \) values in the range 6900 – 7300 K (Van Reeth et al. 2013) and that the hybrid stars are expected to be found at the intersection of the γ Dor and δ Sc括 instability strips, where \( T_{\text{eff}} \) changes approximately from 6600 to 7300 K. Given that the typical \( T_{\text{eff}} \) uncertainty is ∼300 K (Niemczura et al. 2017) and hot γ Dor stars definition by Balona et al. (2016), we selected γ Dor and hybrid candidates with \( T_{\text{eff}} \geq 7500 \) K.

In the end, our selection contained nine hot γ Dor and fifteen hot hybrid candidate stars (Table 1), for which high-resolution spectroscopy was not available. Some of them were observed with low-resolution spectroscopy (Frasca et al. 2016; Balona et al. 2016), but it is not possible to obtain reliable \( \log g \) and metallicity values from this technique.

The positions of the targets in the \( \log T_{\text{eff}} - \log g \) diagram are shown in Fig. 1. As can be seen from the figure, all stars are located beyond the blue edge of γ Dor instability strip. The \( T_{\text{eff}} \) values of the selected targets were also checked by using the updated parameters of the stars (Mathur et al. 2017, hereafter M17). It turned out that all targets except KIC11508397 (∼400 K cooler) still have \( T_{\text{eff}} \) values in the same range of the selection criteria. We used the M17 parameters in the following investigations.

### 3 SPECTROSCOPIC OBSERVATIONS

The stars were observed with the Fibre-fed Échelle Spectrograph (FIES), a cross-dispersed spectrograph mounted on the 2.56-m Nordic Optical Telescope of the Roque de los Muchachos Observatory in La Palma (Telting et al. 2014). The spectrograph offers three resolving power options. The maximum resolving power is \( R = 67 000 \), while the medium and low resolving powers are \( R = 46 000 \) and \( R = 25 000 \), respectively, covering the wavelength range of 3700 – 8300 Å.

Since we aimed to derive atmospheric parameters and chemical abundances of the targets, we opted for the medium-resolution (\( R = 46 000 \)) configuration, taking into account the average brightness of the sample (\( V = 10.6 \) mag). Observations were performed in the first halves of the nights from October 13 to 19, 2016. To examine the binarity nature of the targets, we tried to take at least two spectra per star on different nights. For some stars, only one spectrum could be taken due to the weather conditions and the limited observing time. The number of the spectra for each star and the signal-to-noise (S/N) ratios at around 5500 Å for combined spectra are given in Table 1.

The spectra were reduced by the dedicated pipeline FIESStool (Telting et al. 2014). The standard reduction procedure was applied. Bias subtraction, correction of flat-field, scattered light extraction, wavelength calibration, and merging of orders were performed for each spectrum. Normalization of the reduced spectra was carried out manually by using the continuum task of the NOAO/IRAF package.

### 4 DETERMINATION OF THE ATMOSPHERIC PARAMETERS

The spectroscopic atmospheric parameters (\( T_{\text{eff}} \), \( \log g \), and \( \xi \)) were determined using the Balmer and iron lines, as done in previous several studies (e.g., Nieva & Przybilla 2010; Tkachenko et al. 2012; Niemczura et al. 2017). The approach we used in the analysis of the Balmer lines has been successfully applied in other papers (Catanzaro et al. 2011; Catanzaro & Balona 2014; Catanzaro, Ripepi, & Bruntt 2013). In practice, the procedure minimized the difference between observed and synthetic spectra, using the \( \chi^2 \) as goodness-of-fit parameter. Since the rotational velocity affects the profile of the lines, we determined initial estimates of projected rotational velocity (\( v \sin i \)) values by using the least-squares deconvolution (LSD) technique (Donati et al. 1997). The \( v \sin i \) values were measured from the zero positions of the Fourier transform of the mean line profiles (Table A1).

Synthetic spectra were generated in three steps. First, we computed LTE atmospheric models using the ATLAS9 code (Kurucz 1993a). Second, the stellar spectra were then synthesized using SYNTH (Kurucz & Avrett 1981). Third, the spectra were convolved with the instrumental and rotational broadenings.

#### Table 1. Log of the observations (from October 13 to 19, 2016): number of the star (\( N_i \)) used in the paper, KIC ID, V-magnitude, signal-to-noise ratio (S/N), number of taken spectra (\( N_s \)), and input classification (Uytterhoeven et al. 2011).

| \( N_i \) | KIC   | V        [mag] | S/N | \( N_s \) | Input classification |
|---|--------|-----------|-----|-------|---------------------|
| 1 | 2168333 | 10.02    | 90  | 2     | Hybrid              |
| 2 | 3119604 | 10.90    | 50  | 1     | Hybrid              |
| 3 | 3231406 | 10.38    | 85  | 2     | Hybrid              |
| 4 | 3240556 | 10.10    | 75  | 2     | Hybrid              |
| 5 | 3245420 | 10.52    | 75  | 2     | Hybrid              |
| 6 | 3868032 | 10.44    | 70  | 2     | γ Dor               |
| 7 | 4677684 | 10.19    | 85  | 2     | γ Dor               |
| 8 | 4786877 | 10.91    | 60  | 2     | Hybrid              |
| 9 | 5180796 | 10.11    | 85  | 2     | γ Dor               |
| 10| 5630362 | 10.69    | 70  | 2     | γ Dor               |
| 11| 6199731 | 10.94    | 50  | 1     | Hybrid              |
| 12| 6500578 | 10.77    | 80  | 2     | γ Dor               |
| 13| 6776331 | 10.71    | 50  | 1     | Hybrid              |
| 14| 7694191 | 10.94    | 45  | 1     | γ Dor               |
| 15| 7732458 | 10.85    | 75  | 2     | Hybrid              |
| 16| 9052363 | 10.64    | 60  | 2     | Hybrid              |
| 17| 9775385 | 11.05    | 45  | 1     | Hybrid              |
| 18| 10281360| 11.06    | 50  | 1     | γ Dor               |
| 19| 11197934| 10.81    | 60  | 2     | Hybrid              |
| 20| 11199412| 10.90    | 50  | 1     | γ Dor               |
| 21| 11508397| 10.65    | 80  | 2     | Hybrid              |
| 22| 11612274| 10.44    | 85  | 4     | γ Dor               |
| 23| 11718839| 10.73    | 60  | 2     | Hybrid              |
| 24| 11822666| 10.69    | 70  | 2     | Hybrid              |

1 http://iraf.noao.edu/
Table 2. The atmospheric parameters taken from M17 and our $T_{\text{eff}}$ values derived from the analysis of Balmer lines. $E(B - V)$ values (Sect. 7.4) are also listed.

| Number | KIC     | $E(B - V)$ [mag] | $T_{\text{eff, M17}}$ [K] | log $g_{\text{M17}}$ [dex] | $T_{\text{eff, Hlines}}$ [K] |
|--------|---------|------------------|---------------------------|-----------------------------|-----------------------------|
| 1      | 2168333 | 0.03             | 8363±197                  | 3.80±0.36                   | 8000±300                   |
| 2      | 3119604 | 0.03             | 8383±233                  | 4.03±0.14                   | 7900±360                   |
| 3      | 3231406 | 0.02             | 8005±333                  | 3.77±0.22                   | 7600±270                   |
| 4      | 3240556 | 0.03             | 8615±274                  | 3.78±0.13                   | 8000±300                   |
| 5      | 3245420 | 0.11             | 8079±334                  | 3.72±0.11                   | 7900±320                   |
| 6      | 3868032 | 0.10             | 8564±402                  | 4.04±0.16                   | 8300±610                   |
| 7      | 4677684 | 0.22             | 8602±77                   | 3.78±0.11                   | 8600±480                   |
| 8      | 4768677 | 0.20             | 8584±86                   | 3.76±0.03                   | 8800±830                   |
| 9      | 5180796 | 0.15             | 8076±96                   | 3.82±0.09                   | 8100±280                   |
| 10     | 5630362 | 0.11             | 7821±88                   | 3.88±0.07                   | 7700±170                   |
| 11     | 6199731 | 0.05             | 8040±206                  | 3.64±0.05                   | 7500±320                   |
| 12     | 6500578 | 0.28             | 8072±223                  | 3.72±0.02                   | 8200±450                   |
| 13     | 6776331 | 0.08             | 8780±244                  | 3.70±0.04                   | 7600±400                   |
| 14     | 7694191 | 0.19             | 8070±321                  | 3.66±0.09                   | 8300±580                   |
| 15     | 7732458 | 0.02             | 7766±324                  | 3.64±0.09                   | 7300±230                   |
| 16     | 9052363 | 0.11             | 8110±324                  | 3.74±0.12                   | 7800±360                   |
| 17     | 9775385 | 0.05             | 7675±314                  | 4.05±0.10                   | 7300±300                   |
| 18     | 10281360| 0.06             | 7776±216                  | 4.02±0.22                   | 7200±280                   |
| 19     | 11197934| 0.06             | 7641±58                   | 3.83±0.22                   | 7600±360                   |
| 20     | 11199412| 0.02             | 7693±209                  | 3.72±0.06                   | 7200±280                   |
| 21     | 11508397| 0.00             | 7287±76                   | 3.87±0.18                   | 7200±240                   |
| 22     | 11612274| 0.00             | 7694±214                  | 3.60±0.14                   | 7000±190                   |
| 23     | 11718839| 0.03             | 8443±234                  | 3.76±0.12                   | 8100±500                   |
| 24     | 11822666| 0.03             | 8615±238                  | 3.78±0.14                   | 8200±540                   |

$T_{\text{eff}}$ was estimated by computing the ATLAS9 model atmosphere which gave the best match between the observed $H_{\alpha}$, $H_{\beta}$, $H_{\gamma}$, and $H_{\delta}$ lines profile and those computed with SYNTHE. The models were computed using solar opacity distribution functions (ODF). It is also known that Balmer lines are not sensitive to log $g$ parameter for $T_{\text{eff}} \lesssim 8000$ K (Smalley et al. 2002). Considering the $T_{\text{eff}}$ range of our targets and the error bars, we fixed the log $g$ and metallicity values to 4.0 dex and solar, respectively.

The Balmer lines are located far from the edges of the échelle orders. The simultaneous fitting of four lines led to a final solution at the intersection of the four $\chi^2$ iso-surfaces. An important source of uncertainty arose from difficulties in the normalization since it is always challenging for Balmer lines in échelle spectra. The uncertainties on the $T_{\text{eff}}$ values were estimated by introducing a 1σ change in the normalization level and a 0.2 dex error on log $g$ and metallicity. We also considered the errors on the initial $v \sin i$ values (Table A1). These uncertainties were summed in quadrature with the errors obtained by the fitting procedure. The final results for $T_{\text{eff}}$ values and their errors are reported in Table 2.

Final atmospheric parameters were derived by using the excitation and the ionisation potentials of metal lines. For the correct atmospheric parameters of a star, all lines of the same element should give the same chemical abundance. The relationship between the chemical abundance and the excitation, ionisation potentials of the same element should be flat.

We used Fe lines in the analysis, since they are the most numerous lines in the spectra having the $T_{\text{eff}}$ range of our stars. The ATLAS9 (Kurucz 1993) and model atmospheres were synthesized by using the SYNTHE code (Kurucz & Avrett 1981) in this and the following chemical abundance analysis. A synthetic spectrum is adjusted until it fits well the observed spectrum looking at the $\chi^2$ parameter (for more details see Niemczura et al. 2012; Kahraman Aliçavuş et al. 2016). The Fe lines of all stars were analysed for a range of $T_{\text{eff}}$, log $g$, and $\xi$ with a step of 100 K, 0.1 dex and 0.1 km s$^{-1}$, respectively. The range of the atmospheric parameters was selected taking into account the initial $T_{\text{eff}}$ values derived from Balmer lines and the values given by M17 (Table 2). After the analysis was performed, we determined $T_{\text{eff}}$ and log $g$ values considering the excitation potential–abundance and the ionisation potential–abundance relations, respectively. The $\xi$ values were also obtained by checking the dependence between abundance and line strength. The obtained atmospheric parameters are given in Table 3. The uncertainties in the parameters were estimated by checking how much the parameters change for ~5% differences in the excitation potential–abundance, ionisation potential–abundance, and the abundance–line strength relationships.

The distributions of the derived atmospheric parameters are shown in Fig. The final $T_{\text{eff}}$, log $g$, and $\xi$ ranges were obtained to be 7200 – 8600 K, 3.5 – 4.4 dex, and 1.5 – 4.4 km s$^{-1}$, respectively. The final atmospheric parameters were compared with the M17 atmospheric parameters. In most cases $T_{\text{eff}}$ values are consistent with each other within errors. However, in Fig. the final log $g$ values were
Figure 2. Distributions of the final atmospheric parameters determined from the iron lines analysis and $v\sin i$ values.

Figure 3. Differences between the final spectroscopic log $g$ and the log $g$ taken from M17 as a function of the final spectroscopic $T_{\text{eff}}$ (upper panel) and log $g$ (lower panel) obtained from the iron line analysis. Dashed lines represent 1-$\sigma$ levels. The Spearman’s rank correlation coefficient (R) and probability (the number after comma) are given in the right corner of the right panel.

Figure 4. The final $\xi$ as a function of the final spectroscopic $T_{\text{eff}}$ (right panel) and log $g$ (left panel).

decrease with increasing log $g$. However, as our sample spans a $T_{\text{eff}}$ range narrower than the A5–G2 one, we could not verify these relationships (Fig. 3).

5 ANALYSIS OF CHEMICAL ABUNDANCES

Chemical abundances of the stars were derived by performing spectrum synthesis. The derived atmospheric parameters were taken as input during the analysis and the chemical abundances of individual elements were determined in addition to $v\sin i$.

In the first step of the analysis, all lines in the spectra were divided into subsets line by line. In the case of rapidly rotating stars, lines are mostly blended. Therefore, for rapidly rotating stars wider ranges in wavelength were selected considering the normalisation level. For each subset the line identifications were done by using the line list of Kurucz.

Then these spectral subsets were analysed separately. The identified elements in each spectral subset and $v\sin i$ values were adjusted during the analysis. Taking the minimum difference between the observed and theoretical spectra, chemical abundances and $v\sin i$ values were obtained from each spectral subset. The range of $v\sin i$ was found to be from 49 to 267 km s$^{-1}$ (Table 3, Fig. 2).

The average values of the abundances of individual elements for each star are given in Table A3 and the uncer-
Table 3. The final atmospheric parameters derived from the iron lines analysis, the $v \sin i$ values and the Fe abundances. The final pulsation type classification is given in last column as a result of our frequency analysis.

| Number | KIC     | $T_{\text{eff}}$ [K] | log $g$ [dex] | $\xi$ [km s$^{-1}$] | log $\epsilon$ (Fe) [dex] | $v \sin i$ [km s$^{-1}$] | Pulsation type |
|--------|---------|----------------------|---------------|-----------------|---------------------|---------------------------|----------------|
| 1      | 2168333 | 8400 ± 200           | 3.7 ± 0.2     | 2.0 ± 0.5       | 7.47 ± 0.27         | 175 ± 9                   | $\delta$ Sct     |
| 2      | 3119604 | 7700 ± 200           | 3.9 ± 0.3     | 2.9 ± 0.2       | 7.23 ± 0.34         | 92 ± 5                    | $\delta$ Sct     |
| 3      | 3231406 | 7900 ± 100           | 3.8 ± 0.2     | 2.1 ± 0.2       | 7.63 ± 0.31         | 169 ± 10                  | Hybrid          |
| 4      | 3240556 | 7800 ± 200           | 4.4 ± 0.2     | 1.5 ± 0.5       | 7.51 ± 0.35         | 213 ± 9                   | $\delta$ Sct     |
| 5      | 3245420 | 8100 ± 200           | 3.7 ± 0.1     | 2.0 ± 0.2       | 7.58 ± 0.32         | 151 ± 6                   | $\delta$ Sct     |
| 6      | 3868032 | 8400 ± 200           | 4.0 ± 0.3     | 3.5 ± 0.4       | 7.11 ± 0.32         | 181 ± 9                   | Non-pulsator     |
| 7      | 4677684 | 8500 ± 200           | 3.5 ± 0.2     | 1.7 ± 0.3       | 7.52 ± 0.28         | 71 ± 3                    | $\gamma$ Dor    |
| 8      | 4768677 | 8600 ± 300           | 4.2 ± 0.3     | 2.0 ± 0.5       | 6.94 ± 0.50         | 256 ± 14                  | $\delta$ Sct     |
| 9      | 5180796 | 8400 ± 200           | 4.0 ± 0.2     | 2.5 ± 0.2       | 7.73 ± 0.30         | 152 ± 6                   | $\gamma$ Dor    |
| 10     | 5630362 | 7700 ± 300           | 3.7 ± 0.3     | 3.0 ± 0.5       | 7.34 ± 0.33         | 230 ± 12                  | $\gamma$ Dor    |
| 11     | 6199731 | 7800 ± 200           | 4.1 ± 0.3     | 4.4 ± 0.4       | 7.23 ± 0.35         | 236 ± 10                  | $\delta$ Sct     |
| 12     | 6500578 | 7700 ± 300           | 3.8 ± 0.2     | 1.9 ± 0.3       | 7.35 ± 0.30         | 95 ± 6                    | $\gamma$ Dor    |
| 13     | 6776331 | 7900 ± 200           | 3.9 ± 0.1     | 2.3 ± 0.2       | 7.65 ± 0.32         | 49 ± 3                    | Hybrid          |
| 14     | 7694191 | 8400 ± 200           | 4.1 ± 0.2     | 3.9 ± 0.2       | 7.31 ± 0.36         | 76 ± 6                    | $\gamma$ Dor    |
| 15     | 7732458 | 7800 ± 200           | 4.1 ± 0.2     | 2.6 ± 0.2       | 7.73 ± 0.34         | 87 ± 5                    | $\delta$ Sct     |
| 16     | 9052363 | 8000 ± 200           | 4.1 ± 0.2     | 3.5 ± 0.3       | 7.40 ± 0.33         | 109 ± 5                   | Non-pulsator     |
| 17     | 9775385 | 7400 ± 200           | 4.2 ± 0.2     | 4.1 ± 0.2       | 7.44 ± 0.36         | 71 ± 3                    | Hybrid          |
| 18     | 10281360| 7200 ± 200           | 4.2 ± 0.2     | 4.1 ± 0.3       | 7.29 ± 0.36         | 108 ± 5                   | $\gamma$ Dor    |
| 19     | 11197934| 7600 ± 200           | 3.9 ± 0.2     | 3.0 ± 0.5       | 7.46 ± 0.31         | 267 ± 18                  | Hybrid          |
| 20     | 11199412| 7200 ± 200           | 4.1 ± 0.2     | 3.9 ± 0.3       | 6.68 ± 0.35         | 77 ± 6                    | $\gamma$ Dor    |
| 21     | 11509397| 7200 ± 200           | 3.9 ± 0.3     | 1.5 ± 0.5       | 7.68 ± 0.30         | 240 ± 11                  | Hybrid          |
| 22     | 11612274| 7400 ± 200           | 3.8 ± 0.1     | 3.2 ± 0.2       | 7.38 ± 0.27         | 130 ± 7                   | $\gamma$ Dor    |
| 23     | 11718839| 8100 ± 200           | 3.9 ± 0.1     | 3.4 ± 0.2       | 7.45 ± 0.32         | 57 ± 3                    | $\delta$ Sct     |
| 24     | 11822666| 8200 ± 200           | 4.0 ± 0.1     | 2.5 ± 0.2       | 7.37 ± 0.31         | 115 ± 7                   | Hybrid          |

Figure 5. Differences between the derived chemical abundances and the Solar values [Asplund et al. 2009] as a function of elements for KIC11199412. Filled circles show the differences that were obtained from at least 5 and more lines, while others represent the opposite.

Figure 6. Differences between the spectroscopic [Fe/H] and [Fe/H] taken from H14 as a function of the spectroscopic [Fe/H] (left panel) and $T_{\text{eff}}$ (right panel). The Spearman’s rank correlation coefficient (R) and probability (the number after comma) are given in the right corner of the right panel.
6 FREQUENCY ANALYSIS OF PHOTOMETRIC DATA

To precisely classify the pulsational behaviour of the selected targets, we performed an independent frequency analysis of the Kepler data. The original time series were retrieved from the MAST archive. Keeping the subdivision into long- and short-cadence acquisition mode, the original data were normalized to the mean values of each quarter, thus correcting instrumental drifts. During this procedure isolated outliers were removed. When reconstructing the pulsational content of our variables, we used the short-cadence time series to investigate the region above the Nyquist frequency \( f = 24.5 \, \text{d}^{-1} \) of the more numerous long-cadence data.

The accurate time series were then analysed for their constituent frequencies with the goal to establish their modal content. We have used the iterative both sine-wave fitting method (Vaniček 1971) and the software package Period04 (Lenz & Breger 2005). The final goal is to determine the pulsational characteristics with respect to the spectroscopic properties and the position in the H-R diagram. The initial variability classification of our targets (\( \gamma \) Dor, hybrid) was taken from Uytterhoeven et al. (2011). When our analysis was almost finished, Murphy et al. (2019) used Gaia–derived luminosities to propose another classification scheme based on the skewness of the amplitudes in the Fourier spectra. However, these authors focused on the \( \delta \) Sct stars, without investigating the frequency region below \( 5 \, \text{d}^{-1} \), where \( \gamma \) Dor and hybrid stars are expected to show their \( g \)-modes.

6.1 Variability not induced by pulsation

The most obvious case was that of KIC 3868032. The frequency spectrum clearly shows peaks at \( f = 0.40 \, \text{d}^{-1} \), \( 2f \), \( 3f \), and \( 4f \). The spectroscopic analysis pointed out a mean profile with two superimposed components, with clearly different rotational regimes, i.e., \( v \sin i = 180 \, \text{km} \, \text{s}^{-1} \) and \( v \sin i < 100 \, \text{km} \, \text{s}^{-1} \). Uytterhoeven et al. (2011) classified it as a \( \gamma \) Dor variable. However, these peaks are associated with the orbital motion and cannot be ascribed to pulsation. We noticed that after considering \( f \) and harmonics, a peak at \( f_1 = 1.68 \, \text{d}^{-1} \) appears, close but not equal to \( 4f \). It could be still an artifact of the orbital/rotational effects, but its pulsational origin cannot be ruled out.

The case of KIC 9052363 is similar. The light curve is almost flat, without any clear feature that could be ascribed to pulsation. The frequency analysis reveals a couple of low-frequency, very-low amplitude peaks. Due to their incoherence, small rotational effects are the most plausible reason. Both stars are also reported as non-\( \delta \) Sct by Murphy et al. (2019).

6.2 Low-frequency regime

Eight stars in our sample show a set of low-frequency peaks only. We ordered them by increasing frequency of the strongest peak (Fig. 7). We note that the range of frequencies is small, not exceeding \( 6 \, \text{d}^{-1} \). Occasional high frequency peaks appear in the frequency spectra not enough to claim that a clear double regime of pulsation is present. It is noteworthy that all stars in Fig. 7 were classified as \( \gamma \) Dor by Uytterhoeven et al. (2011). Actually, they are the only stars classified as \( \gamma \) Dor in our sample and therefore we are in full agreement.

KIC 5630362 is the star showing the highest frequency \( f = 4.856 \, \text{d}^{-1} \), with an amplitude much larger than those of the others (bottom panel). It is unlikely that this frequency is that of the fundamental radial mode, since the long period would suggest an evolved \( \delta \) Sct star: the very fast rotation (230 km s\(^{-1}\)) and the gravity (\( \log g = 3.7 \) dex) do not support such an hypothesis. Therefore, pulsators with largely predominant modes also exist in \( \gamma \) Dor stars.

Figure 7. Amplitude spectra obtained by combining short- and long-cadence data of the variables showing a regime of low-frequency \( (f \leq 6 \, \text{d}^{-1}) \) modes. They are ordered for increasing frequency of the highest peak.

\[ \text{http://archive.stsci.edu/} \]
Figure 8. Amplitude spectra obtained by combining short- and long-cadence data of the variables showing a prevailing regime of high-frequency modes. They are ordered for increasing frequency of the highest peak.

not only in δ Sct ones (i.e., the Group A proposed by Murphy et al. 2019).

6.3 High-frequency regime

None of the stars in our sample was classified as a pure δ Sct star. However, our frequency analysis showed that some stars are characterized by a large set of high-frequency peaks accompanied by no (or a few) low-frequency ones (Fig. 8). The case of KIC 3240556 is noteworthy, since this star shows a largely predominant mode. The frequency is too high \( f = 25.2 \text{ d}^{-1} \) to be due to rotation. Note that the short-cadence time series allowed us to determine the exact value of this high frequency very close to the Nyquist frequency of the long-cadence data. KIC 3240556 surely belongs to Group A in the Murphy et al. (2019) classification scheme.

All these variables were classified as hybrid stars. However, we know from the analysis of line-profile variations that very high-degree modes (up to \( \ell = 14 \)) are excited in δ Sct stars and they are spectroscopically detectable (Poretti et al. 2009; Mantegazza et al. 2012). The rotational splitting can shift the frequencies of retrograde modes of multiplets toward low values, thus producing the bunch of peaks observed there in hybrid stars. They also could be combination terms between high-frequency modes or again effects of the rotational modulation induced by changing spots and/or faculae on the stellar surfaces. We emphasize that in general this multiplicity of causes does not make a few low-frequency peaks on their own a sufficient criterion to claim for an hybrid pulsational regime.

6.4 Low and high-frequency regime

Only six stars show simultaneously well-defined low- and high-frequency regimes (Fig. 9), with clear peaks in both regions. However, it has to be noted how the amplitude spectra differ: there are low- and high-frequencies both confined in separated groups and continuously distributed. All these stars had an input classification as hybrid variables.

7 DISCUSSION

We can now use the results from the frequency and atmospheric analyses to better define the properties of our targets and closely look at how much they are really peculiar, as suggested by previous works. Our new classification and parameters are reported in Table 3. In the left panel of Fig. 10 the
log $T_{\text{eff}}$ – log $g$ positions are shown on the basis of the predicted atmospheric parameters by M17, while in the right panel our final atmospheric parameters are used. As can be noticed, the larger changes in the positions are mostly due to the differences in the log $g$ values.

7.1 Binary nature

Composite spectra suggesting double-lined spectroscopic binaries are not observed, except for the ellipsoidal variable KIC 38658032 (Sect. 6.1). Seventeen stars in our sample have at least two spectra taken on different nights. The radial velocities were examined: if there was a companion, the radial velocities should vary due to the orbital motion. We did not find any large variation in the radial velocities. Nevertheless, the very small number of observations and their very limited time coverage do not allow us to clearly detect long-period binaries. For time coverage do not allow us to clearly detect long-period binaries. For

7.2 Pulsation characteristics vs new atmospheric parameters

Our detailed frequency analysis was able to clean the physical scenario since 10 targets (8 Sct and 2 non-pulsating stars; Sects. 6.1 and 6.2) out of 24 (42%) can be retired from the initial sample of γ Dor and hybrid pulsators. In particular the 8 Sct stars erroneously classified as hybrid variables turned out to be normal p-modes pulsators, well inside the δ Sct instability strip. Additionally, the two non-pulsators remain located close to the hot border of the δ Sct domain, where the fraction of δ Sct pulsating stars is estimated to be ≲40% [Murphy et al. 2019].

Among the six hybrid variables, only KIC 11199412 is a normal γ Dor pulsator (Sect. 6.1). Seventeen stars in our sample have very long orbital periods (≥350 d; Murphy et al. 2018), but the radial velocities obtained from their two spectra differ by 2.6 and 1.5 km s$^{-1}$ only, respectively.

7.3 Other atmospheric parameters

When the obtained atmospheric parameters are taken into account, most stars are found that they have $T_{\text{eff}}$ values in agreement with those given by M17. Only two stars, KIC 10281360 and KIC 11199412, show spectroscopic $T_{\text{eff}}$ values about 500 K cooler than the previously given values by M17. This explains why the previous classification put them so close to the hot border.

Our final log $g$ values were compared with the log $g$ values given by M17 (Fig. 3). In some cases, the final log $g$ values differ more than 0.4 dex. Therefore, the positions of these stars change in the log $T_{\text{eff}}$ – log $g$ diagram (Fig. 10). When taking into account the final positions in the log $T_{\text{eff}}$ – log $g$ diagram and the evolutionary tracks, we can say that ~70% of stars have masses from 2.0 to 2.5 $M_{\odot}$, while the mass range of the others is between 1.6 and 2.0 $M_{\odot}$.

The microturbulent velocity $\xi$ changes with $T_{\text{eff}}$ (Grav. Graham & Hovl 2001, Smaller 2004, Landstreet et al. 2009) and the $\xi$ value varies from ~1.5 to 3 km s$^{-1}$ for $T_{\text{eff}}$ range of about 7000 – 7300. However, three cool stars (KIC 9775385, KIC 10281360, KIC 11199412) have $\xi$ values between 3.9 and 4.1 km s$^{-1}$ with a maximum uncertainty of 0.3 km s$^{-1}$. These $\xi$ values are high for this $T_{\text{eff}}$ range, but the three stars seem to be normally located on the cool border of the γ Dor instability strip. For the hotter stars the $\xi$ range is between 1.5 and 4.5 (±0.3) km s$^{-1}$, as expected for A-type stars.

Some target stars have low-resolution LAMOST spectroscopy in the literature. The atmospheric parameters derived from these studies are given in Table A2. When we compared these results with our final atmospheric parameters, we found significant differences and trends between the parameters obtained from the high- and low-resolution spectroscopy (Fig. 11).

7.4 Chemical abundances

Anomalous abundances, like the Am phenomenon (Hareter et al. 2011), have been considered a possible physical explanation of the hybrid γ Dor-δ Sct pulsation. Our analysis did not reveal any abundance peculiarity in the bona-fide sample of eight hot γ Dor and hybrid stars, in agreement with recent studies showing that most hybrid stars are chemically normal (Niemczura et al. 2015, 2017). We also searched for He lines, without any significant detection. Only KIC 11199412 (a normal γ Dor star) exhibits a moderate underabundance in almost all the elements (Fig. 4).

7.5 The $v \sin i$ values and the SPB hypothesis

It has been suggested that hot γ Dor stars are actually rapidly-rotating SPB stars (Salmon et al. 2014, Balona et al. 2012, 2016). Due to gravity darkening, their equatorial zones appear cooler than the rest of the surface, then they are classified as hot A-stars and, hence, as hot γ Dor variables.

Balona et al. (2016) determined an average $v \sin i = 114$ km s$^{-1}$ for a group of six hot γ Dor stars. Our five bona-fide hot γ Dor stars show $v \sin i$ values ranging from 71 to 230 km s$^{-1}$ (Table 3), with an average value of...


Figure 10. a) The positions of the target stars, as numbered in Table 3, according to the atmospheric parameters given by M17. b) The positions of the stars according to the final atmospheric parameters. The theoretical instability strips of the $\gamma$ Dor (dashed lines) and $\delta$ Sct (solid lines) stars were taken from Dupret et al. (2005). The evolutionary tracks ($Z=0.02$) were adopted from Kahraman Alıcavuş et al. (2016).

Figure 11. Comparison of the atmospheric parameters obtained from high- and low-resolution spectroscopy. The subscripts $H$ and $L$ defines the high- and low-resolution spectroscopy, respectively. The Spearman’s rank correlation coefficient ($R$) and probability (the number after comma) are given in the right corner of the panels. Blue lines represent the 1σ levels.

of 125 km s$^{-1}$. In the spectral range B5-B9, main-sequence stars, like SPB variables, show a mean $v \sin i = 144$ km s$^{-1}$ (Glebocki & Gnaciński 2003; Balona et al. 2016). Since hot $\gamma$Dor stars do not seem to rotate faster than normal SPB stars, they do not constitute a special SPB subclass. Moreover, we could not find spectral lines indicative of the B-type (Sect. 7.4), which should be present at least for SPB stars seen at intermediate or pole-on orientations. Finally, gravity darkening does not seem to be able to lower the $T_{\text{eff}}$ of SPB stars sufficiently to approach the hot border of the $\delta$ Sct instability strip (see Fig. 4 in Salmon et al. 2014). We prudently note that the classification as hot or classical hybrid/ $\gamma$Dor stars could also be affected by the gravity darkening, especially in case of fast rotators seen almost equator-on, like KIC 5630362, KIC 11197934, and KIC 11508397.

7.6 Gaia parallaxes

As a final check, we used the Gaia parallaxes (Gaia Collaboration et al. 2018) to investigate the positions of the stars in the H-R diagram. We adopted the bolometric corrections computed taking into account the $T_{\text{eff}}$ values (Flower 1996). The extinction coefficients ($A_V$) were estimated using the interstellar reddening $E(B-V)$ values (Table 2). These were obtained by measuring the equivalent widths of the NaD lines in our spectra and then applying the relation given by Munari & Zwitter (1997).

An offset of $-0.03$ mas in the Gaia parallaxes was found (Lindegren et al. 2018; Zinn et al. 2019). However, when this offset was applied to a large sample ($\sim$15000 stars), a huge amount of stars goes below the zero-age main-sequence with unreasonably low luminosities (Murphy et al. 2019). Therefore, to calculate our final Gaia luminosities we did not apply this offset to the parallaxes, accordingly with recent studies (Arenou et al. 2018; Murphy et al. 2019). The positions of the stars in the H-R diagram are illustrated in Fig. 12. Note that the new empirical instability strip of $\delta$ Sct stars (Murphy et al. 2014) now incorporates some variables located beyond the hot border of the previous theoretical instability strip.

As can be noticed from Fig. 12 stars 7, 9, 10, 12, and 14 (see Table 3 for their KIC identification) have very high luminosities. When the radii of those hot $\gamma$ Dor stars were calculated using the Gaia luminosities, we obtained values ranging from 4.3 to 6.0 $R_\odot$. We also calculated the radii
8 CONCLUSIONS

We performed a detailed spectroscopic and photometric study of a group of 24 Kepler targets, all claimed to be hot γ Dor or δ Sct–γ Dor hybrid stars, located well beyond the theoretical γ Dor instability strip (Uytterhoeven et al. 2011). The detailed frequency analysis of the Kepler time series and the determination of $T_{\text{eff}}$ and other atmospheric parameters performed with the new FIES spectra allowed us to set the bona-fide sample of such peculiar pulsators to five hot γ Dor stars and three hot hybrid stars. If on one hand we provide a strong confirmation that these peculiar pulsators exist, on the other we reduce their recurrence to $1/3$ to what originally evaluated. Therefore, we can assume that the physical explanation should reside in a mechanism or a cause applicable to a limited number of stars, not to the vast majority of the δ Sct or γ Dor variables.

Searching for this still elusive explanation, we did not find any peculiarity in the atmospheric parameters and chemical abundances. The lack of composite spectra does not support the possibility that the hot hybrid stars are binaries in which one or both components are normal δ Sct and/or γ Dor pulsators. We investigated the rotation rate and we cannot support the hypothesis that hot γ Dor pulsators are actually fast-rotating SPB stars. On the other hand, Gaia luminosities suggested us that hot γ Dor pulsators have larger radii and higher luminosities than normal main sequence A-F stars. New efforts, both theoretical and observational, have to be made to well constrain all the features of this new scenario.

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Figure 12. The positions of the stars in the H-R diagram, as numbered in Table 1. The theoretical instability strips of the γ Dor (dashed lines) and δ Sct (solid black lines) stars were taken from Dupret et al. (2004). The recently suggested δ Sct instability strip (Murphy et al. 2013) is shown by brown solid lines. The evolutionary tracks $\left(Z=0.02\right)$ were adopted from Kahraman Alicavus et al. (2010).
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Appendix
Table A1. The initial $v \sin i$ values derived for the Balmer lines analysis (Sect. 4) and our spectral classification (Sect. 5).

| KIC   | $v \sin i$ (km s$^{-1}$) | Spectral type |
|-------|------------------------|--------------|
| 216833 | 163 ± 15              | kA5hA4V      |
| 3119604 | 94 ± 1               | A5 V         |
| 3231406 | 173 ± 6              | A7III-IV     |
| 3240556 | 218 ± 4              | A5IV-V       |
| 3245420 | 158 ± 4              | A7 V         |
| 3868032 | 178 ± 4              | A5 V         |
| 4677684 | 75 ± 5               | A3IV-V       |
| 4768677 | 257 ± 14             | A3IV-V       |
| 5180796 | 155 ± 3              | A4IV-V       |
| 5630362 | 242 ± 12             | A5III-IV     |
| 6199731 | 241 ± 3              | A5III        |
| 6500578 | 98 ± 3               | A3IV         |
| 6776331 | 51 ± 1               | A7 V         |
| 7694191 | 78 ± 1               | A5IV-V       |
| 7732458 | 82 ± 2               | A9IV-V       |
| 9052363 | 109 ± 2              | A5IV-V       |
| 9775385 | 72 ± 1               | F0V          |
| 10281360 | 111 ± 4             | A9IV-V       |
| 11197934 | 295 ± 5             | A8IV-V       |
| 11199412 | 73 ± 2            | kA3hF0mA3 V |
| 11508397 | 245 ± 6             | F0V          |
| 11612274 | 132 ± 4             | F0V          |
| 11718839 | 57 ± 4             | kA7hA5mA7 V |
| 11822666 | 121 ± 4             | A5V          |

Table A2. The atmospheric parameters of the stars which have low-resolution spectroscopy in the literature.

| KIC    | $T_{\text{eff}}$ [K] | log $g$ [dex] | Fe/H [dex] | Reference |
|--------|----------------------|---------------|------------|-----------|
| 4677684 | 9245 ± 529          | 3.82 ± 0.13   | −0.19 ± 0.13 | 1         |
| 4768677 | 9655 ± 323          | 3.82 ± 0.12   | −0.22 ± 0.12 | 1         |
| 5180796 | 7981 ± 370          | 3.87 ± 0.13   | −0.12 ± 0.12 | 1         |
| 6199731 | 7390 ± 255          | 3.96 ± 0.13   | −0.08 ± 0.13 | 1         |
| 7694191 | 8140 ± 10           | 3.79          | −0.04       | 2         |
| 9052363 | 7752 ± 320          | 3.90 ± 0.12   | −0.10 ± 0.13 | 1         |
| 9775385 | 7296 ± 137          | 3.89 ± 0.13   | 0.06 ± 0.14  | 1         |
| 10281360 | 7300 ± 10          | 3.91 ± 0.14   | 0.02 ± 0.13  | 1         |
| 11197934 | 7429 ± 205         | 3.90 ± 0.12   | 0.00 ± 0.13  | 1         |
| 11199412 | 11956 ± 1854       | 4.00 ± 0.15   | 0.05 ± 0.16  | 1         |
| 11508397 | 7300 ± 148         | 3.91 ± 0.14   | 0.02 ± 0.13  | 1         |
| 11612274 | 7179 ± 152         | 4.01 ± 0.13   | −0.03 ± 0.13 | 1         |
| 11718839 | 7734 ± 210         | 4.07 ± 0.02   | −0.21 ± 0.01 | 2         |

References: 1. Frasca et al. (2019), 2. Qian, et al. (2019).
Table A3. Average abundances and standard deviations of individual elements. Number of the analysed spectral parts is given in the brackets.

| Atomic number | Elements | KIC 2168333 | KIC 3119604 | KIC 3231406 | KIC 3240556 | KIC 3245420 |
|---------------|----------|-------------|-------------|-------------|-------------|-------------|
| 6             | C        | 8.45 ± 0.18 (1) | 8.54 ± 0.19 (4) | 8.53 ± 0.13 (4) | 8.94 ± 0.20 (2) | 8.51 ± 0.32 (6) |
| 8             | O        | 8.97 ± 0.24 (1) | 5.74 ± 0.24 (1) | 8.05 ± 0.15 (5) | 7.97 ± 0.36 (3) | 7.85 ± 0.50 (6) |
| 11            | Na       | 5.74 ± 0.24 (1) | 8.05 ± 0.15 (5) | 7.97 ± 0.36 (3) | 7.85 ± 0.50 (6) | 7.23 ± 0.28 (3) |
| 12            | Mg       | 7.95 ± 0.39 (6) | 7.82 ± 0.22 (6) | 8.05 ± 0.15 (5) | 7.97 ± 0.36 (3) | 7.85 ± 0.50 (6) |
| 14            | Si       | 6.60 ± 0.18 (2) | 7.18 ± 0.33 (3) | 7.50 ± 0.10 (3) | 6.49 ± 0.20 (2) | 7.23 ± 0.28 (3) |
| 16            | S        | 4.42 ± 0.20 (1) | 4.42 ± 0.20 (1) | 2.11 ± 0.20 (1) | 2.11 ± 0.20 (1) | 4.66 ± 0.32 (1) |
| 20            | Ca       | 6.20 ± 0.28 (12) | 6.96 ± 0.28 (7) | 6.30 ± 0.26 (3) | 6.38 ± 0.35 (7) |
| 21            | Sc       | 3.63 ± 0.32 (3) | 3.65 ± 0.35 (3) | 3.93 ± 0.37 (3) |
| 22            | Ti       | 5.22 ± 0.31 (11) | 5.17 ± 0.23 (9) | 5.40 ± 0.45 (15) |
| 23            | V        | 4.36 ± 0.20 (2) | 5.35 ± 0.23 (1) | 4.91 ± 0.32 (2) |
| 24            | Cr       | 5.96 ± 0.14 (6) | 5.96 ± 0.18 (6) | 5.84 ± 0.23 (9) |
| 25            | Mn       | 5.86 ± 0.20 (2) | 5.45 ± 0.22 (2) | 5.58 ± 0.32 (2) |
| 26            | Fe       | 7.23 ± 0.16 (45) | 7.63 ± 0.18 (33) | 7.51 ± 0.24 (14) | 7.58 ± 0.18 (31) |
| 28            | Ni       | 6.94 ± 0.20 (2) | 5.93 ± 0.20 (2) | 6.69 ± 0.32 (2) |
| 29            | Cu       | 4.22 ± 0.20 (1) | 4.22 ± 0.20 (1) | 4.03 ± 0.32 (1) | 4.66 ± 0.32 (1) |
| 30            | Zn       | 4.42 ± 0.20 (1) | 4.42 ± 0.20 (1) | 4.03 ± 0.32 (1) | 4.66 ± 0.32 (1) |
| 38            | Sr       | 1.97 ± 0.18 (1) | 1.54 ± 0.22 (1) | 2.11 ± 0.20 (1) |
| 39            | Y        | 4.64 ± 0.22 (1) | 4.80 ± 0.20 (1) | 4.03 ± 0.32 (1) | 4.66 ± 0.32 (1) |
| 40            | Zr       | 2.22 ± 0.22 (1) | 2.22 ± 0.22 (1) | 4.03 ± 0.32 (1) | 4.66 ± 0.32 (1) |
| 56            | Ba       | 2.74 ± 0.18 (1) | 1.97 ± 0.22 (2) | 2.89 ± 0.20 (2) | 3.27 ± 0.32 (1) | 3.43 ± 0.32 (1) |

Table A3. Continuation.

| Atomic number | Elements | KIC 3868032 | KIC 4677684 | KIC 4768677 | KIC 5180796 | KIC 5630362 |
|---------------|----------|-------------|-------------|-------------|-------------|-------------|
| 6             | C        | 8.30 ± 0.20 (1) | 8.60 ± 0.27 (2) | 7.99 ± 0.13 (1) | 8.66 ± 0.10 (5) | 8.74 ± 0.31 (1) |
| 8             | O        | 8.31 ± 0.24 (1) | 8.83 ± 0.25 (1) | 4.22 ± 0.20 (1) | 4.22 ± 0.20 (1) | 4.03 ± 0.32 (1) | 4.66 ± 0.32 (1) |
| 11            | Na       | 7.93 ± 0.16 (4) | 7.85 ± 0.33 (8) | 8.10 ± 0.13 (5) | 7.87 ± 0.51 (5) | 6.45 ± 0.31 (2) |
| 12            | Mg       | 6.25 ± 0.11 (10) | 6.96 ± 0.28 (7) | 6.55 ± 0.28 (9) | 5.85 ± 0.46 (3) |
| 14            | Si       | 5.74 ± 0.35 (7) | 7.44 ± 0.21 (5) | 6.45 ± 0.31 (2) |
| 16            | S        | 6.57 ± 0.20 (1) | 6.25 ± 0.11 (10) | 6.96 ± 0.28 (7) | 6.55 ± 0.28 (9) | 5.85 ± 0.46 (3) |
| 20            | Ca       | 3.52 ± 0.17 (4) | 3.63 ± 0.32 (3) | 3.49 ± 0.32 (5) | 2.15 ± 0.31 (1) |
| 21            | Sc       | 5.22 ± 0.31 (11) | 5.36 ± 0.32 (14) | 4.99 ± 0.13 (6) |
| 22            | Ti       | 4.36 ± 0.20 (2) | 4.81 ± 0.25 (2) | 4.99 ± 0.13 (6) |
| 23            | V        | 5.72 ± 0.24 (15) | 5.11 ± 0.14 (5) | 5.93 ± 0.12 (10) | 5.59 ± 0.21 (6) |
| 24            | Cr       | 5.73 ± 0.44 (3) | 5.50 ± 0.26 (3) | 4.38 ± 0.31 (1) |
| 25            | Mn       | 5.72 ± 0.24 (15) | 5.11 ± 0.14 (5) | 5.93 ± 0.12 (10) | 5.59 ± 0.21 (6) | 4.38 ± 0.31 (1) |
| 26            | Fe       | 6.08 ± 0.48 (3) | 6.51 ± 0.26 (4) | 6.51 ± 0.26 (4) |
| 28            | Ni       | 2.61 ± 0.27 (1) | 1.99 ± 0.25 (1) |
| 29            | Cu       | 2.22 ± 0.27 (2) | 3.83 ± 0.25 (1) | 3.22 ± 0.25 (1) |
| 30            | Zn       | 1.98 ± 0.20 (1) | 2.48 ± 0.20 (2) | 2.44 ± 0.25 (2) | 2.71 ± 0.31 (1) |
### Table A3. Continuation.

| Atomic number | Elements | KIC 6199731 | KIC 6500578 | KIC 6776331 | KIC 7694191 | KIC 7732458 |
|---------------|----------|-------------|-------------|-------------|-------------|-------------|
| 6             | C        | 8.72 ± 0.23 (1) | 8.41 ± 0.15 (8) | 8.71 ± 0.27 (7) | 8.76 ± 0.27 (5) | 8.79 ± 0.15 (7) |
| 8             | O        | 8.68 ± 0.32 (2) | 6.54 ± 0.32 (1) | 6.48 ± 0.28 (1) | 8.20 ± 0.28 (2) | 6.48 ± 0.28 (1) |
| 11            | Na       | 7.00 ± 0.23 (3) | 7.84 ± 0.29 (8) | 8.03 ± 0.12 (7) | 7.68 ± 0.18 (3) | 8.24 ± 0.26 (5) |
| 12            | Si       | 6.67 ± 0.23 (2) | 6.97 ± 0.48 (9) | 7.07 ± 0.32 (10) | 6.90 ± 0.49 (4) | 7.59 ± 0.28 (10) |
| 16            | S        | 5.88 ± 0.39 (3) | 6.40 ± 0.30 (11) | 6.86 ± 0.28 (21) | 6.27 ± 0.18 (8) | 6.73 ± 0.35 (21) |
| 20            | Ca       | 2.69 ± 0.23 (1) | 3.12 ± 0.35 (4) | 3.22 ± 0.22 (6) | 3.12 ± 0.21 (7) | 3.45 ± 0.31 (7) |
| 22            | Ti       | 4.97 ± 0.25 (9) | 5.00 ± 0.23 (22) | 5.43 ± 0.22 (37) | 5.23 ± 0.25 (27) | 5.45 ± 0.31 (30) |
| 23            | V        | 3.90 ± 0.35 (3) | 4.58 ± 0.29 (4) | 4.66 ± 0.21 (3) | 5.01 ± 0.28 (4) | 5.01 ± 0.28 (4) |
| 24            | Cr       | 5.62 ± 0.26 (7) | 5.65 ± 0.26 (18) | 5.80 ± 0.30 (29) | 5.65 ± 0.27 (13) | 6.01 ± 0.30 (30) |
| 25            | Mn       | 4.73 ± 0.23 (2) | 5.11 ± 0.61 (6) | 5.46 ± 0.23 (9) | 5.58 ± 0.42 (6) | 5.83 ± 0.21 (10) |
| 26            | Fe       | 7.23 ± 0.10 (15) | 7.35 ± 0.17 (47) | 7.65 ± 0.16 (102) | 7.31 ± 0.25 (59) | 7.73 ± 0.21 (89) |
| 28            | Ni       | 6.37 ± 0.43 (12) | 6.25 ± 0.32 (21) | 6.18 ± 0.25 (7) | 6.51 ± 0.38 (32) | 6.51 ± 0.38 (32) |
| 29            | Cu       | 2.38 ± 0.23 (1) | 2.55 ± 0.21 (3) | 3.22 ± 0.31 (1) | 1.98 ± 0.24 (1) | 3.09 ± 0.18 (2) |

### Table A3. Continuation.

| Atomic number | Elements | KIC 9052363 | KIC 9775385 | KIC 10281360 | KIC 11197934 | KIC 11199412 |
|---------------|----------|-------------|-------------|-------------|-------------|-------------|
| 6             | C        | 8.80 ± 0.14 (3) | 8.75 ± 0.10 (6) | 8.75 ± 0.25 (4) | 8.95 ± 0.37 (1) | 8.62 ± 0.21 (2) |
| 8             | O        | 8.96 ± 0.24 (1) | 8.67 ± 0.25 (1) | 8.16 ± 0.25 (1) | 8.34 ± 0.21 (1) | 8.34 ± 0.21 (1) |
| 11            | Na       | 7.56 ± 0.10 (4) | 7.96 ± 0.17 (5) | 7.48 ± 0.22 (5) | 8.09 ± 0.37 (2) | 6.68 ± 0.14 (3) |
| 12            | Mg       | 7.23 ± 0.23 (6) | 7.16 ± 0.38 (21) | 7.01 ± 0.10 (3) | 7.04 ± 0.37 (2) | 6.07 ± 0.21 (2) |
| 16            | S        | 6.99 ± 0.24 (2) | 6.37 ± 0.29 (17) | 6.35 ± 0.19 (9) | 6.27 ± 0.52 (5) | 5.86 ± 0.24 (5) |
| 20            | Ca       | 6.20 ± 0.22 (8) | 6.94 ± 0.22 (12) | 2.96 ± 0.12 (6) | 4.35 ± 0.70 (3) | 2.18 ± 0.21 (2) |
| 22            | Ti       | 5.04 ± 0.34 (23) | 5.06 ± 0.22 (40) | 4.86 ± 0.31 (29) | 5.05 ± 0.23 (8) | 4.64 ± 0.35 (19) |
| 23            | V        | 4.36 ± 0.22 (2) | 4.71 ± 0.19 (6) | 4.03 ± 0.28 (4) | 4.35 ± 0.37 (1) | 3.67 ± 0.12 (3) |
| 24            | Cr       | 5.64 ± 0.26 (13) | 5.75 ± 0.19 (26) | 5.46 ± 0.29 (15) | 5.75 ± 0.18 (8) | 5.03 ± 0.21 (7) |
| 25            | Mn       | 5.45 ± 0.13 (3) | 5.66 ± 0.30 (11) | 5.16 ± 0.25 (2) | 5.38 ± 0.37 (2) | 5.03 ± 0.13 (4) |
| 26            | Fe       | 7.40 ± 0.19 (42) | 7.44 ± 0.17 (90) | 7.29 ± 0.14 (48) | 7.46 ± 0.21 (15) | 6.68 ± 0.24 (36) |
| 28            | Ni       | 6.35 ± 0.17 (6) | 6.33 ± 0.36 (27) | 6.12 ± 0.14 (13) | 6.35 ± 0.37 (1) | 5.73 ± 0.24 (3) |
| 29            | Cu       | 3.50 ± 0.24 (2) | 3.13 ± 0.24 (2) | 2.51 ± 0.31 (5) | 2.56 ± 0.63 (4) | 2.36 ± 0.21 (2) |
| 30            | Zn       | 2.11 ± 0.22 (1) | 2.51 ± 0.31 (5) | 2.45 ± 0.25 (2) | 3.66 ± 0.37 (2) | 1.47 ± 0.21 (2) |
| Atomic number | Elements | KIC 11508397 | KIC 11612274 | KIC 11718839 | KIC 11822666 |
|---------------|----------|--------------|--------------|--------------|--------------|
| 6             | C        | 8.89 ± 0.31 (1) | 8.30 ± 0.22 (6) | 8.64 ± 0.15 (6) | 8.95 ± 0.37 (1) |
| 8             | O        | 8.82 ± 0.25 (1) | 8.82 ± 0.25 (1) | 8.82 ± 0.25 (1) | 8.82 ± 0.25 (1) |
| 11            | Na       | 8.17 ± 0.21 (4) | 7.86 ± 0.10 (4) | 7.93 ± 0.18 (5) | 8.09 ± 0.37 (2) |
| 12            | Mg       | 6.72 ± 0.31 (2) | 7.41 ± 0.10 (3) | 7.25 ± 0.40 (10) | 7.04 ± 0.37 (2) |
| 14            | Si       | 7.73 ± 0.41 (4) | 6.57 ± 0.39 (9) | 6.45 ± 0.15 (17) | 6.27 ± 0.52 (5) |
| 16            | S        | 5.21 ± 0.34 (7) | 4.96 ± 0.28 (19) | 5.17 ± 0.15 (40) | 5.05 ± 0.23 (8) |
| 20            | Ca       | 4.13 ± 0.31 (1) | 4.04 ± 0.25 (2) | 4.40 ± 0.25 (2) | 4.35 ± 0.37 (1) |
| 21            | Sc       | 5.69 ± 0.36 (5) | 5.50 ± 0.28 (12) | 5.75 ± 0.17 (24) | 5.75 ± 0.18 (8) |
| 22            | Ti       | 5.07 ± 0.31 (1) | 5.34 ± 0.25 (2) | 5.64 ± 0.14 (5) | 5.38 ± 0.37 (2) |
| 23            | Cr       | 7.68 ± 0.19 (23) | 7.38 ± 0.14 (36) | 7.45 ± 0.15 (106) | 7.46 ± 0.21 (15) |
| 24            | Mn       | 6.31 ± 0.31 (2) | 6.09 ± 0.34 (10) | 6.21 ± 0.14 (15) | 6.35 ± 0.37 (1) |
| 25            | Fe       | 1.65 ± 0.31 (1) | 3.09 ± 0.24 (1) | 2.53 ± 0.12 (3) | 2.53 ± 0.12 (3) |
| 26            | Ni       | 2.23 ± 0.31 (2) | 2.21 ± 0.19 (3) | 2.21 ± 0.19 (3) | 2.21 ± 0.19 (3) |
| 27            | Cu       | 3.36 ± 0.10 (2) | 3.11 ± 0.19 (4) | 3.11 ± 0.19 (4) | 3.11 ± 0.19 (4) |
| 28            | Sr       | 1.84 ± 0.31 (1) | 2.73 ± 0.17 (2) | 2.24 ± 0.10 (3) | 3.66 ± 0.37 (2) |