Spectrum Analysis of Bright Kepler $\gamma$ Doradus Candidate Stars

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ABSTRACT

Ground-based spectroscopic follow-up observations of the pulsating stars observed by the Kepler satellite mission are needed for their asteroseismic modelling. We aim to derive the fundamental parameters for a sample of 26 $\gamma$ Doradus candidate stars observed by the Kepler satellite mission to accomplish one of the required preconditions for their asteroseismic modelling and to compare our results with the types of pulsators expected from the existing light curve analysis. We use the spectrum synthesis method to derive the fundamental parameters like $T_{\text{eff}}$, $\log g$, $[M/H]$, and $v \sin i$ from newly obtained spectra and compute the spectral energy distribution from literature photometry to get an independent measure of $T_{\text{eff}}$. We find that most of the derived $T_{\text{eff}}$ values agree with the values given in the Kepler Input Catalogue. According to their positions in the HR-diagram three stars are expected $\gamma$ Dor stars, ten stars are expected $\delta$ Sct stars, and seven stars are possibly $\delta$ Sct stars at the hot border of the instability strip. Four stars in our sample are found to be spectroscopic binary candidates and four stars have very low metallicity where two show about solar C abundance. Six of the 10 stars located in the $\delta$ Sct instability region of the HR-diagram show both $\delta$ Sct and $\gamma$ Dor-type oscillations in their light curves implying that $\gamma$ Dor-like oscillations are much more common among the $\delta$ Sct stars than predicted by theory. Moreover, seven stars showing periods in the $\delta$ Sct and the $\delta$ Sct-$\gamma$ Dor range in their light curves are located in the HR-diagram left of the blue edge of the theoretical $\delta$ Sct instability strip. The consistency of these findings with recent investigations based on high-quality Kepler data implies the need for a revision of the theoretical $\gamma$ Dor and $\delta$ Sct instability strips.

Key words: Stars: variables: delta Scuti – Stars: fundamental parameters – Stars: abundances.

1 INTRODUCTION

The Kepler satellite was launched in March 2009 with the primary goal to search for transiting exoplanets in the solar neighbourhood. It delivers single band-pass light curves of micromagnitude precision and has found hundreds of planet candidates [Borucki et al. 2011]. The long, uninterrupted, and high-precision time series photometry taken for a huge number of stars has also led to the discovery of many new pulsating stars and is an ideal basis for an in-depth asteroseismic analysis (see e.g. Gilliland et al. 2010). For this analysis and the subsequent asteroseismic modelling, precise knowledge of the fundamental parameters of the stars is essential. These parameters cannot be determined from the single band-pass photometry delivered by Kepler alone, however. Hence, ground-based spectroscopic follow-up observations have been undertaken to determine the stellar parameters.

In this paper, we are concerned with $\gamma$ Doradus candidates found from data assembled with the Kepler mission. Such pulsators are named after their prototype, Gamma Doradus, whose multiperiodic variable nature was first reported by Cousins (1992). Krisciunas et al. (1993) discovered a multiperiodic photometric variability with an amplitude of about 0.1 mag and periods of 2.275 and 1.277 d in 9 Aurigae and reported on similar behaviour in $\gamma$ Doradus and HD 96008. Following these discoveries, Balona et al. (1994)...
introduced a new class of variable stars named after the prototy- 
pe star γ Doradus. γ Dor stars are assumed to pulsate in high-
order, low-degree non-radial gravity modes driven by the flux 
blocking mechanism near the base of their convective zones 
(Guzik et al. 2004; Dupret et al. 2005). The typical masses of 
these stars lie in the range of 1.5–1.8 M⊙ (Aerts et al. 2010). 
According to Kaye et al. (1999), γ Dor-type stars can be charac-
terised as follows: (1) spectral type A7–F5 and luminosity class IV, IV-V, or V, (2) low-
amplitude photometric variations with periods between 0.5 
and 3 days as well as spectroscopic variability seen as both 
line-profile and low-amplitude radial velocity (RV) varia-
tions and gives the Kepler Input Catalog (KIC) number, an 
alternative designation, the number of obtained spectra, the 
visual magnitude, the spectral type as is indicated in the 
Journal of observations. N gives the number of obtained 
spectra, V - the visual magnitude. All spectra have been taken in 
2010.

<table>
<thead>
<tr>
<th>KIC</th>
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<td>9.6</td>
<td>A2</td>
<td>August</td>
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Dor stars are located close to the red edge of the clas-
sical instability strip in the HR-diagram. The theoretical γ 
Dor instability strip overlaps with the red edge of classi-
cal instability strip where the δ Scut pulsators are located. While the low-order p-modes of δ Scut stars are characteriz-
ed by short periods ranging from 18 min to 8 h, typical γ 
Dor high-order g-modes have periods of the order of a day 
(e.g., Aerts et al. 2010). Multiperiodicity is found for most of 
the γ Dor class members from ground-based photometry 
(Henry et al. 2007; Cuypers et al. 2009) and spectroscopy 
(e.g., Mathias et al. 2004; De Cat et al. 2006). Pulsators in 
the overlapping region of the δ Scand γ Dor instability strip 
are expected to show the two pulsation characteristics, i.e., 
high-order g-modes probing the core and low-order p- and 
g-modes probing the outer layers. While the frequency pat-
terns of these two types of oscillations are in principle easy 
to distinguish in the co-rotating frame of reference, the fre-
quencies start to overlap in an inertial frame of reference, 
particularly for the fast rotators. Moreover, the overall beat-
ing patterns are complex and hard to unravel from inter-
rupted ground-based data. Some hybrid pulsators were al-
ready found previously (e.g., Rowe et al. 2006; King et al. 
2007), but the Kepler data make it clear that hybrid pul-
sators turn out to be numerous, both for AF-type stars 
(Uytterhoeven et al. 2011b; Balona et al. 2011a) and for B-
type stars (Balona et al. 2011b).

Gray & Kaye (1993) were the first to report a connec-
tion between the λ Bootis (λ Boo) type stars and the γ Dor 
variables. λ Boo stars are Pop I hydrogen burning metal poor 
(except of C, N, O, and S) A-type stars (Paunzen et al. 
1997; Paunzen 2004) showing significant underabundances 
of Fe-peak elements (up to ~2 dex compared to the solar 
composition). They belong to the class of non-magnetic, 
chemically peculiar stars. Up to now, only two further re-
ports (Sadakane 2006; Rodriguez et al. 2007) on a possible 
connection between the λ Boo stars and γ Dor-type variabil-
ity appeared. A recent analysis of a sample of 18 γ Dor stars 
performed by Bruntt et al. (2008) revealed no principal dif-
ference between the abundances of the analysed stars and 
the chemical composition of non-pulsating A- and F-type 
stars.

In this paper, we investigate a sample of 26 among the 
brighter stars in the Kepler field which have been pro-
tected for candidates for γ Dor variables (Uytterhoeven et al. 
2011a). We aim to evaluate fundamental stellar parameters 
like effective temperature T eff, surface gravity log g, projected 
rotational velocity v sin i, and microturbulent velocity ξ as 
well as the chemical composition of the target stars 
from newly obtained high-resolution spectra. Based on the 
derived parameters, we present a classification of the sam-
ple stars according to the expected type of variability. The 
derived chemical composition in turn allows to check for 
a possible connection between γ Dor-type variability and 
λ Boo-type abundance patterns.

2 OBSERVATIONS

We base our analysis on high-resolution, high signal-to-noise 
ratio (S/N) spectra taken with the Coudé-Echelle spectro-
graph attached to the 2-m telescope of the Thüringer Land-
esternwarte Tautenburg, Germany. The spectra have a 
resolution of 32000 and cover the wavelength range from 
4720 to 7400 Å. Table 1 represents the journal of observa-
tions and gives the Kepler Input Catalog (KIC) number, an 
alternative designation, the number of obtained spectra, the 
visual magnitude, the spectral type as is indicated in the 
SIMBAD database, and the period of observation in 2010. 
The number of acquired spectra is different for different stars 
since we aimed to reach a S/N of about 100 for the mean, 
averaged spectrum of each object.

The data have been reduced using standard ESO-
MIDAS packages. The data reduction included bias 
and stray-light subtraction, cosmic rays filtering, flat fielding 
by a halogen lamp, wavelength calibration by a ThAr lamp, 
and normalisation to the local continuum. All spectra were addi-
tionally corrected in wavelength for individual instrumental 
shifts by using a large number of telluric O2 lines. The cross-
correlation technique was used to estimate the RVs from the
individual spectra so that the single spectra finally could be shifted and added to build the mean, high S/N ratio averaged spectrum of each star. The RVs computed at this step have also been used to check for possible variations due to binary, high-amplitude stellar oscillations and rotational modulation.

3 SPECTRAL ANALYSIS

3.1 Method

The “classical” method of spectrum synthesis by means of equivalent width measurements and subsequent fitting of the ionization equilibria of different elements requires the star to rotate slowly, so that a sufficient number of clean, unblended spectral lines can be identified and measured in the stellar spectrum. In the case of rapidly rotating stars, this method fails due to the high percentage of blended lines. The method of spectrum synthesis, on the other hand, is based on the comparison between observed and theoretical spectra in a certain wavelength range. Its advantage is that the effect of line blending can be taken into account when computing the synthetic spectra and thus no restrictions with respect to the rotational velocity occur. Because of the large number of fast rotators in our sample, we use the second method comparing the observed spectra with a huge number of synthetic spectra computed on a grid in the stellar parameters. Against the much faster approach of solving the so-called inverse problem, i.e. to determine the physical parameter values directly from the observations using some non-linear optimization method, the grid search has the advantage that it will always determine the globally best solution if the grid is dense enough. Its principal disadvantage of much longer computing time plays no crucial role in our analysis since
the synthetic spectra are calculated using a large library of pre-computed model atmospheres (Table 3) and the analysis runs very fast on up to 300 processor cores of a cluster PC.

Our code GSSP (Grid Search in Stellar Parameters) finds the optimum values of effective temperature $T_{\text{eff}}$, surface gravity log $g$, microturbulent velocity $\xi$, metallicity $[M/H]$, and projected rotational velocity $v \sin i$ from the minimum in $\chi^2$ obtained from a comparison of the observed spectrum with the synthetic ones computed from all possible combinations of the before mentioned parameters. The errors of measurement ($1\sigma$ confidence level) are calculated from the $\chi^2$ statistics. A detailed description of the method is given in [Lehmann et al. 2011] (Paper I).

For the calculation of synthetic spectra, we use the LTE-based code SynthV ([Tsymbal 1996]) which allows the computation of spectra based on individual elemental abundances. 

The code uses pre-calculated atmosphere models which have been computed with the most recent, parallelised version of the LLmodels program ([Shulyak et al. 2004]). Both programs make use of the VALD database ([Kupka et al. 2000]) for a pre-selection of atomic spectral lines. The main limitation of the LLmodels code is that the models are well suitable for early and intermediate spectral type stars but not for very hot and cool stars where non-LTE effects or absorption in molecular bands may become relevant, respectively.

Table 3. Derived metallicity and elemental abundances relative to solar ones in dex. Asterisks indicate elements with error estimates of $\pm 0.10$ dex ($\pm 0.20$ dex in all other cases). Metallicity values labeled with “(Fe)” refer to the derived Fe-abundance.
Table 4. \(E(B-V)\) determined from the Na D lines, \(T_{\text{eff}}\) obtained from SED-fitting, and the reddening-corrected \(T_{\text{eff}}\).

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<tr>
<th>KIC</th>
<th>(E(B-V))</th>
<th>(T_{\text{eff}})</th>
<th>(T_{\text{eff}}) (dered)</th>
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<td>0.04</td>
<td>7650±160</td>
<td>7910±250</td>
</tr>
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<td>7650±150</td>
<td>7840±240</td>
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<td>6840±190</td>
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<tr>
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<td>12353648</td>
<td>0.02</td>
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Figure 1. Comparison of \(T_{\text{eff}}\) derived spectroscopically (open circles) with the KIC (filled boxes) and photometric values (open triangles and stars). See text for detailed description.

Table 5. Stellar atmosphere models computed with the LLmodels code for \(\xi = 2 \text{ km s}^{-1}\).

<table>
<thead>
<tr>
<th>Parameter, step width</th>
<th>([M/H])</th>
<th>(\Delta[M/H])</th>
<th>(T_{\text{eff}}) (K)</th>
<th>(\Delta T_{\text{eff}}) (K)</th>
<th>(\log g)</th>
<th>(\Delta \log g)</th>
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<td>(-0.8 \rightarrow 0.8)</td>
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<td>4500–10000</td>
<td>100</td>
<td>2.5–5.0</td>
<td>0.1</td>
<td>3.9–5.0</td>
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<td>10000–22000</td>
<td>250</td>
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</table>

Total number of models: 41 888

3.2 Results

Table 2 summarises the results of spectrum analysis for all 26 stars of our sample. The first four columns of the table represent correspondingly the KIC-number of a star, the effective temperature \(T_{\text{eff}}\), surface gravity \(\log g\), and metallicity \([M/H]\) as is indicated in the KIC. The five following columns list the stellar parameters derived from our spectra, while the last two columns represent the spectral types as estimated from \(T_{\text{eff}}\) and \(\log g\) given in the KIC and determined in this work, respectively. In both cases, the spectral types and the luminosity classes have been derived using an interpolation in the tables by [Schmidt-Kaler (1982)](https://example.com). We achieve a mean accuracy of about 1% for \(T_{\text{eff}}\), about ±0.16 dex for \(\log g\), and about 5% for \(\sin i\).

Table 4 lists the elemental abundances derived for each target star. The metallicity given in the second column of the table refers to the initially derived chemical composition and was used as initial guess for the determination of the individual abundances. All abundances are given relative to solar values, i.e. negative/positive values refer to an under-/overabundance of the corresponding element compared to the solar composition. We assume the chemical composition of the Sun given by [Grevesse et al. (2007)](https://example.com) and these values are listed in the header of Table 3 below the element designations. For some of the stars we have reached the metallicity limit in our grid of atmosphere models ([KIC03217554, 03453494, 09812351, and 12353648](https://example.com)). In these cases, we give the derived Fe-abundance instead of the metallicity. In all other cases, the derived Fe abundance matches the derived metallicity within the measurement error. The abundance errors are estimated to be about ±0.1 dex for the elements showing a sufficient number of strong spectral lines in the considered region and about ±0.2 dex for the elements represented in the spectrum by only few and rather faint spectral lines.

3.3 Special characteristics of some target stars

The derived \(T_{\text{eff}}\) and \(\log g\) are discussed in Sect. 5. Here, we focus on metallicity and abundance anomalies based on Table 3 and on possible binarity of the target stars.

Stars of lower metallicity. Only three stars in our sample of 26 show metallicities slightly higher than the Sun; all other stars have lower metallicity. Fifteen stars have a metallicity of more than 0.3 dex lower than the Sun. The four stars of lowest metallicity ([KIC03217554, 03453494, 09812351, and 12353648](https://example.com)) show underabundances of the Fe-peak elements and Ca of about 1 dex but much less for Mg and Si. Two of them ([KIC09812351 and 12353648](https://example.com)) have
C abundances comparable to the solar value, resembling the characteristics of λ Boo stars.

*Abundance anomalies.* For eleven of the analysed stars the Ba abundance is found to deviate by more than 0.4 dex from the derived metallicity. In only one of them Ba is underabundant, all other are Ba enhanced. Since the Ba abundance is found to deviate by more than 0.4 dex from the derived metallicity.

Table 6. The stars for which remarkable differences in the individual RVs are observed.

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<th>RV</th>
<th>dRV</th>
<th>max. diff</th>
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<td></td>
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<td>(km s(^{-1}))</td>
<td>(km s(^{-1}))</td>
</tr>
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<td>0.129</td>
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<td>338.560657</td>
<td>−0.248</td>
<td>0.285</td>
<td></td>
</tr>
<tr>
<td>09 413 057</td>
<td>340.573022</td>
<td>−5.208</td>
<td>0.104</td>
<td></td>
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<tr>
<td>10 119 517</td>
<td>428.472508</td>
<td>−110.03</td>
<td>0.066</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2. Fit of observed spectra (solid, black line) by synthetic spectra calculated from our optimised parameters (dashed, red line) and from the values given in the KIC (dotted, green line), showing either the H\(\beta\) line. A colour plot is provided in the online version.

4 SPECTRAL ENERGY DISTRIBUTIONS

The effective temperature can also be determined from the spectral energy distribution (SED). For our target stars we constructed SEDs using literature photometry from 2MASS [Skrutskie et al. 2006], Tycho [Hög et al. 1997], TASS [Droege et al. 2006], USNO-B1 [Monet et al. 2003] and UCAC3 [Zacharias et al. 2010]. \(T_\text{eff}\) was determined by...
fitting solar-composition Kurucz (1993) model fluxes to the photometry. The model fluxes were convolved with the photometric filter response functions. A weighted Levenberg-Marquardt non-linear least-squares fitting procedure was used to find the solution that minimised the difference between the observed and model fluxes. Since log \( g \) is poorly constrained due to lack of UV flux measurements, we fixed log \( g = 4.0 \) for all the fits. This introduces additional errors of about 50 K into the determined effective temperature for the stars showing significant deviations from the assumed value of log \( g \).

Since spectral energy distributions can be significantly affected by interstellar reddening, we measured the equivalent widths of the interstellar Na D lines if present in our spectra and determined \( E(B-V) \) using the relation given by Munari & Zwitter (1997). Table 4 lists the results. Columns 3 and 4 correspondingly give the temperature values derived without and with the effects of interstellar reddening taken into account.

5 COMPARISON WITH THE KEPLER INPUT CATALOGUE

Figure 1 compares the spectroscopically derived \( T_{\text{eff}} \) with the photometric and KIC values (typical errors of the KIC data are \( \pm 200 \) K for \( T_{\text{eff}} \) and \( \pm 0.5 \) dex for both log \( g \) and metallicity). The stars are sorted by the spectroscopic \( T_{\text{eff}} \) value starting with the coolest object. For most of the targets we find a rather good agreement between the spectroscopically determined temperature (open circles) and the value listed in the KIC (filled boxes). Whereas in most cases the \( T_{\text{eff}} \) from the uncorrected SED fit (open triangles) is slightly lower than the spectroscopic one, the temperatures corrected for the interstellar reddening (asterisks) show rather a good agreement. In the following, we discuss stars that show larger deviations from this general tendency in \( T_{\text{eff}} \) based on Fig. 1 or large deviations from the KIC values in the other parameters based on Table 2.

KIC 05 446 068: The spectroscopically derived temperature exceeds the KIC value by 400 K and the de-reddened photometric one by 700 K. Our fit with the best synthetic spectrum is rather poor and the spectrum of a second star can clearly be seen in the residuals. We assume the star to be a SB2 star so that none of the derived temperatures may be valid.

KIC 06 587 551: According to the spectroscopic findings, this is the hottest star of our sample, in agreement with the photometrically evaluated \( T_{\text{eff}} \) corrected for the interstellar reddening. Both the KIC and the uncorrected photometric values are by about 500 K lower. This is an interesting fact since we already showed in Paper I that, for the hotter stars (\( T_{\text{eff}} > 8000 \) K), the KIC values of \( T_{\text{eff}} \) are systematically lower than the spectroscopic ones, suggesting that the reason may be that the interstellar reddening was not properly taken into account when deriving the KIC temperatures.

KIC 04 847 411: This example shows that the parameters listed in the KIC can be unreliable. Figure 2 (top panel) compares the observed H\( \beta \) line profile (solid, black line) with the synthetic ones computed from the parameters derived by us (dashed, red line) and from those listed in the KIC.
(dotted, green line). Obviously, the green spectrum does not match the observations at all. Since the metallicity value of −1.95 listed in the KIC is much lower than the limiting value in our grid of atmosphere models, we expect the deviation from the observations to be even larger, in particular for all metal lines. Our spectra show RV variations with an amplitude of about 5.5 km s$^{-1}$ and a period of about 10 d. We need more spectra to reveal the nature of this variability.

KIC 08738 244: This star shows a large discrepancy between the derived values of log $g$ and [M/H] and those listed in the KIC. Figure 2 (second panel) compares the observed spectrum with synthetic spectra in one metal line region and shows that the model based on the KIC values gives no reliable fit. The same is the case for the Balmer line profiles.

KIC 09 812 351 and 12 353 648: these are metal poor stars with metallicities below the limit of our grid of atmosphere models. Both show overabundances of C, Mg, and Si compared to the Fe abundance, while the spectrum of KIC 12 353 648 additionally exhibits a strong depletion of Ti. The derived metallicities, represented in this case by the Fe abundance, are much lower than the values listed in the KIC and KIC 12 353 648 additionally shows a discrepancy of about 300 K in $T_{\text{eff}}$. The effect of the different parameter sets on the synthetic spectra is illustrated in two lower panels of Figure 2.

Figure 3 shows the positions of all stars of our sample in the log $(L/L_{\odot})$ vs. $T_{\text{eff}}$ diagram, together with the δ Sct and γ Dor instability strips. The latter were reconstructed from Dupret et al. (2003, Figures 2 and 9). The edges of the δ Sct instability region have been computed with a mixing-length parameter of $\alpha=1.8$ for the fundamental mode (solid thin lines) and for a radial order of $n=4$ (solid thick lines). The edges of the γ Dor instability regions computed with $\alpha=2.0$ and 1.5 are represented by dashed thin and thick lines, respectively. To place the stars into the diagram, we estimated their luminosities from the spectroscopically derived $T_{\text{eff}}$ and log $g$ by means of an interpolation in the tables by Schmidt-Kaler (1982). The luminosity error bars represent a combination of the errors in $T_{\text{eff}}$ and log $g$, and so in some cases they appear to be significantly larger than the uncertainties in $T_{\text{eff}}$. Beside that, the luminosity errors can still be underestimated due to the uncertainties in the empirical relations. Realizing that, we base our classification mainly on the position of the stars in the HR-diagram according to the derived temperatures.

6 THE STARS IN THE HR-DIAGRAM

Table 7 classifies the stars according to their type of variability, listing the classifications expected from their location in the HR-diagram (Fig. 3) and derived by Uytterhoeven et al. (2011b) from the frequency analysis of the Kepler light curves. There are six “outliers” in the log $(L/L_{\odot})$ vs. $T_{\text{eff}}$ diagram (Fig. 3). Three of them (labels c, f, and h) are suspected binaries and two (labels w and y) are the stars for which no reliable fit of the observed spectrum could be obtained. For these objects we cannot give a certain classification. For the remaining, sixth object, KIC 10 119 517 (label u), no pulsations could be found from the light curve analysis.

For most stars of our sample, the classification based on the light curve analysis appears to be fully consistent with the position of the objects in the log $T_{\text{eff}}$ vs. log $(L/L_{\odot})$ diagram. We confirm three γ Dor stars (labels a, b, and g), and 10 δ Sct pulsators lying in the expected region of the HR-diagram. Four of them, however, have been classified by Uytterhoeven et al. (2011b) as hybrid pulsators although they do not fall in the overlapping region between the γ Dor and δ Sct stars in our HR-diagram. One star, KIC 04 847 411, was not analyzed by Uytterhoeven et al. (2011b). Its light curve classification listed in Table 7 is based on our own analysis of the first Quarter of Kepler data.

There are ten further stars that show δ Sct-like oscillations in their light curves. Six of them have been classified by Uytterhoeven et al. (2011b) as hybrid pulsators but do not fall in the overlapping region in the HR-diagram. Five stars (labels i, j, m, p, and x) are close to the hot border of the δ Sct instability region, two other ones (labels l and r) are distinctly hotter than given by this border. Four stars are too cool (labels h, w) or too evolved (labels c, f) to be hybrid, γ Dor or δ Sct pulsators.

Four stars of our sample are reported by Uytterhoeven et al. (2011b) to be binaries. Three of them could be identified as SB2 stars. For the fourth one, more observations are needed to confirm its binarity spectroscopically.

Fifteen of the analysed targets show metallicities which are lower by more than 0.3 dex than the metallicity of the Sun. The four stars of lowest metallicity show underabundances of about 1 dex. Two of them, KIC 09 812 351 and 12 353 648, have a C abundance comparable to the solar value which might be a sign of λ Boo nature. Additionally to the C abundance, this type of variable stars is characterised by solar abundances of N, O and S. We did not find any spectral lines of these elements in the considered wavelength range that could be used for an abundance determination, however. We also find that most of the analysed stars are rather fast rotators with projected rotational velocities above 90 km s$^{-1}$.

7 CONCLUSIONS

We determined the fundamental parameters of 26 stars in the Kepler satellite field of view proposed to be candidates for γ Dor-type variables (Uytterhoeven et al. 2011a). The analysis was done by means of the spectrum synthesis method based on the comparison between the observed and synthetic spectra. As an additional test of the derived $T_{\text{eff}}$, we computed SEDs by using photometry from literature and determined $T_{\text{eff}}$ by fitting solar-composition Kurucz (1993) model fluxes to the photometric data.

A comparison of the results from the different methods was made. Besides some outliers, where the reasons can be explained, the $T_{\text{eff}}$ derived from the spectrum analysis shows a good overall agreement with the values given in the KIC. For the hottest star of our sample, the KIC value appears to be underestimated. This agrees with our finding in Paper I that the $T_{\text{eff}}$ given in the KIC are in general too low for the hotter stars because the interstellar reddening was not properly taken into account. The $T_{\text{eff}}$ following from the SED fitting are systematically lower. This can be explained by the interstellar reddening. Our correction for this effect
by using the equivalent widths of the interstellar Na D lines to derive $E(B-V)$, improves the situation although in some cases the resulting $T_{\text{eff}}$ is found to be slightly overestimated. The accuracy of the values for $\log g$ and $[M/H]$ in the KIC is rather poor. An uncertainty of ±0.5 dex is stated in the catalogue for both parameters, in some cases we also find larger deviations from our analysis so that the values given in the catalogue are not suited to check for the quality of our findings.

The spectroscopically derived fundamental parameters allow us to place the stars in a HR-diagram and to compare their location with the classification made by Grigahcène et al. (2010) who investigated a sample of 234 Doradus Candidate Stars. Similar to our results, they found a significant number of hybrid pulsators, whereas the theoretical hybrid pulsators that certainly fall into the $\delta$ Sct instability region we could find an explanation either by binary nature or insufficient convergence of the parameter determination.

We find three stars (labels a, b, and g) out of the 14 stars that show oscillations in their light curves typical for $\gamma$ Dor or $\gamma$ Dor-$\delta$ Sct hybrid pulsators that certainly fall into the $\delta$ Sct range of the diagram. Ten further stars are found to be located in one of the $\delta$ Sct regions of the HR-diagram, six of them show $\delta$ Sct and in four $\delta$ Sct and $\gamma$ Dor-typical oscillations coexist. This shows that oscillations with periods in the $\gamma$ Dor range are much more common among the $\delta$ Sct stars than described by the theoretical $\gamma$ Dor instability region. This finding is in agreement with Grigahcène et al. (2010) who investigated a sample of 234 Kepler stars and found a significant number of hybrid pulsators, whereas theory predicts the existence of hybrids in only a small overlapping region of the instability strips.

We find seven stars close to the left or left of the blue edge of the $\delta$ Sct instability strip calculated for fourth radial overtone pulsations. Only two of these stars show $\delta$ Sct-like oscillations but five of them show oscillations with periods in the $\delta$ Sct and in the $\gamma$ Dor range. Similar to our results, Grigahcène et al. (2010) found a significant number of stars showing $\delta$ Sct or $\delta$ Sct-$\gamma$ Dor oscillations which are hotter than predicted by the theoretical blue edge of the $\delta$ Sct instability strip calculated for fourth radial overtone pulsations.

We found four stars with very low metallicities in the -1 dex range. Two of them have about solar C abundance which could be a sign of $\lambda$ Boo nature. Both stars show $\delta$ Sct-like but no $\gamma$ Dor-typical oscillations. Thus we did not find any hint for a relationship between the $\lambda$ Boo stars and $\gamma$ Dor-type variability in our sample.

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REFERENCES

Cousins, A. W. J. 1992, The Observatory, 112, 53
Rodríguez E., Suárez J. C., Moya A., et al., 2007, Communications in Asteroseismology, 150, 131
Rowe J. F., Matthews J. M., Cameron C., et al., 2006, Communications in Asteroseismology, 148, 34
Sadakane K., 2006, PASJ, 58, 1023
Schmidt-Kaler Th., 1982, in Landolt-Börnstein, ed. K. Schaifers, & H. H. Voigt (Springer-Verlag), 2b
Zacharias N., Finch C., Girard T., et al., 2010, AJ, 139, 2184