

Periodic variable A-F spectral type stars in the northern TESS continuous viewing zone

I. Identification and classification

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Received September 15, 1996; accepted March 16, 1997

ABSTRACT

Context. In the time of large space surveys that provide tremendous amount of precise data, it is highly desirable to have a commonly accepted methodology and system for the classification of the variable stars. This is important especially for A-F stars that can show brightness variations due to both rotation and pulsations.

Aims. The goal of our study is to provide a reliable classification of variability of A-F stars brighter than 11 mag located in the northern TESS continuous viewing zone. We also aim at thorough discussion about issues in the classification related to the data characteristics and the issues rising from the similar light curve shape generated by different physical mechanisms.

Methods. We used TESS long- and short-cadence photometric data and corresponding Fourier transform to classify the variability type of the stars. We also used spectroscopic observations to get projected rotational velocity of a few stars.

Results. We present a clear and concise classification system that is demonstrated on many examples. We found clear signs of variability in 3025 of 5923 studied stars (51 %). For 1813 of these 3025 stars we provide a classification, the rest would have been ambiguously classified. From the classified stars, 64.5 % are pulsating stars of GDOR and DSCT types and their hybrids. We realized that the long- and short-cadence PDCSAP data can differ significantly not only in amplitudes but also in the content of instrumental/data reduction artifacts making the long-cadence data less reliable. We identified a new group of stars showing stable light curves and characteristic frequency spectra pattern (8.5 % of the classified stars). According to the position in the Hertzsprung-Russell diagram, these stars are likely GDOR stars but are about 200 K cooler than GDOR in average and have smaller amplitudes and longer periods in average. With the help of spectroscopic measurements of $v \sin i$, we show that variability of stars having unresolved groups of peaks located close to the positions of the harmonics in their frequency spectra (16 % of the classified stars) can rather be caused by rotation than by pulsations. We show that without spectroscopic observations, it can be impossible to unambiguously distinguish between ellipsoidal variability and rotational variability. We also apply our methodology to three previous studies and found significant discrepancies in the classification.

Conclusions. We demonstrate how difficult the classification of variable A-F stars can be when using only photometric data, how the residual artifacts can produce false positives and that some types cannot be actually distinguished without spectroscopic observations. Our analysis provides a trustworthy collections that can be used as training samples for automatic classification.

Key words. Stars: variables: general – Stars: oscillations – Stars: rotation – Catalogs

1. Introduction

The photometric space missions have provided us with an invaluable insight into the mechanisms that produce variations in brightness. The ultra-precise data are especially important in the region of the Hertzsprung-Russell diagram where A-F stars are located ($6000 < T_{\text{eff}} < 10000$ K). It is the location where we can observe transition between slow and fast rotation of stars, energy

transfer via radiation and convection, and transition between complex local magnetic fields and stable fossil fields. Stars in this region can also pulsate, both in acoustic p - and gravity g -modes.

We can, thus, observe various types of variability, often present at the same time. Among A-F pulsating stars, we can find high-order g -mode γ Doradus (GDOR) type pulsations with periods in the order of hours to days (Balona et al. 1994; Kaye

et al. 1999) generated by the convective-flux blocking mechanism (Guzik et al. 2000; Dupret et al. 2005), δ Scuti (DSCT) low-radial order p -mode pulsators (Breger 2000) with pulsations excited by the opacity mechanism in the He II layer (Cox 1963; Breger 2000) and by turbulent pressure (Houdek 2000; Antoci et al. 2014) with periods of hours. There are also hybrid stars showing both DSCT and GDOR pulsations (Henry & Fekel 2005; Handler 2009; Grigahcène et al. 2010; Sánchez Arias et al. 2017). Similar pulsational characteristics to DSCT have SX Phe stars that are Population II stars, while DSCT stars are Population I stars (Balona & Nemeč 2012). The last type of pulsations appearing among of A-F stars are p -mode oscillations with periods in the order of minutes observed in rapidly oscillating (roAp) stars (Kurtz 1982).

Photometric variation can be also caused by rotation. In stars with stable atmospheres, light elements (e.g., He) can settle down and other (usually Si and rare-earth elements such as Sr, Cr, Eu) can be levitated to the surface and create chemical spots (Michaud 1970; Preston 1974). In presence of magnetic field, these spots can be sustained and cause rotational modulation (Stibbs 1950; Kochukhov 2011). In some of the A-F type stars, variability similar to solar activity and spots was observed (Balona 2013). Among rotationally variable stars, we can find also ellipsoidal variables, i.e. stars in non-eclipsing binary system that are tidally deformed and due to gravitational darkening they can also show brightness variations as the stars orbit around the common center of mass (Morris 1985; Beech 1985). For the completeness, we should not forget to mention also classical variable stars such as RR Lyrae stars and systems containing the intrinsic variable stars mentioned above, such as eclipsing binaries and exoplanetary candidates. Flare-like events have also been observed in A-type stars (Balona 2012). However, Pedersen et al. (2017) found out that the flares can come from a nearby stars and companions in binary systems putting doubts on the flares among A-type stars.

The classification of variable stars observed by space missions is usually based on the common light-curve characteristics and on the characteristics of the frequency spectra (e.g. Debosscher et al. 2011; Uytterhoeven et al. 2011b; Balona et al. 2011; Balona 2011; Bradley et al. 2015). Most of the classifications are being performed semi-automatically employing visual inspection. Nowadays, with the tremendous increase of the data, automatic procedures using (supervised) machine learning and neural networks are being developed (e.g. Debosscher et al. 2011; Audenaert et al. 2021). Although there are some basic common criteria, the classification methodology is not unified and the classification can differ. In addition, due to the data quality and data characteristics, and/or similar manifestation of different physical mechanisms, ambiguity in classification can emerge. Therefore, it is important to properly identify the physical mechanisms and classify the stars to better understand the physical limits and physical background.

In this paper, we investigate A-F stars observed by the TESS space mission (Ricker et al. 2015) near the northern ecliptic pole (Sect. 2 and 3). The time base of the TESS observations of the stars in this region is the longest available providing great opportunity for the most reliable classification of periodically variable stars and studying changes with periods in the order of days to tens of days. We perform a careful case-by-case visual classification of the variability type of every particular star using 30- and 2-minute cadence data and provide a large catalogue of variable stars. The trigger for the classification was the identification of interesting targets for the detail study. However, the detailed

investigation of particularly interesting targets is a topic for separate paper(s).

Significant portion of the paper is dedicated to the discussion about effects having impact on the identification of variability, false variability connected with the instrumental/data reduction artifacts and how the data itself affect the results (Sect. 4, 5 and 6). We describe in detail criteria adopted for the classification and discuss ambiguities among different variability types (Sect. 6). Results of our analysis are given in Sect. 7. The summary of the paper and future prospects are in Sect. 8.

2. TESS observations and data products

The heart of the TESS satellite consists of four cameras with four 2K×2K CCDs each that produce combined field of view (FOV) of $24^\circ \times 96^\circ$ (Ricker et al. 2015). Due to large FOV the angular resolution per pixel is only $21''/\text{px}$. The part of the sky that is observed for two consecutive TESS orbits ($\sim 2 \times 13.7$ days) around the Earth is called 'sector'. After the observation of the sector is finished, the FOV moves 27° along the ecliptic for the next sector. The whole hemisphere is scanned in a 'cycle'. TESS avoids regions closer than 6° to the ecliptic plane to eliminate the disruptive light of the Solar system bodies and the Moon. Such an observing strategy means that the sectors overlap around the ecliptic poles (TESS Continuous Viewing Zone, hereafter "TESS CVZ") providing almost uninterrupted observations with the time base of about 350 days. Such data are the most suitable for the investigation of the stellar variability.

The full frame images (FFIs) are downloaded each 30 minutes (long-cadence, from now on "LC") providing photometry for all observed objects down to 16-17 mag, while the dedicated postage-stamp images (target pixel files, TPF) of selected targets are being downloaded each 2 minutes (short-cadence, from now on "SC"). The TPF and the light curves processed by the TESS Science Processing Operations Center (SPOC, Jenkins et al. 2016) are available at the Mikulski Archive for Space Telescopes (MAST)¹. SPOC provides two kinds of photometric data - Simple Aperture Photometry (SAP) and Pre-search Data Conditioning SAP flux with long-term trends removed (PDCSAP, Twicken et al. 2010). At MAST, also products from the Quick-Look Pipeline (QLP, Huang et al. 2020a,b) with the 30-min sampling are available.

3. Sample selection and data retrieval

To select stars that are close to the TESS CVZ, we first cross-matched the TESS Input Catalogue (TIC) v8.0 (Stassun et al. 2019) with the Simbad database (Wenger et al. 2000) around the Northern ecliptic pole ($RA=18^{\text{h}}00^{\text{m}}00^{\text{s}}$, $DEC=+66^\circ 30' 00''$) with the radius of 15 deg using CDS X-Match service (Boch et al. 2012; Pineau et al. 2020). The cross match with the Simbad database gives a good chance that there is some available information about the stars in literature in case of the need. The initial sample for our work consists of 67093 stars in and close to the TESS CVZ.

In the next step, we limited our sample to stars with $6000 < T_{\text{eff}} < 10000$ K to get only stars with A-F spectral types². We also limited our sample to stars with brightness less than 11 mag in Johnson V filter to select only stars with good quality data that are bright enough to be suitable for the spectroscopic observations with 1-meter class telescopes and further studies.

¹ <https://archive.stsci.edu/>

² We used T_{eff} from the TIC catalogue (Stassun et al. 2019)

Table 1. Distribution of the number of stars in particular temperature and brightness ranges of the sample stars (from the TIC, Stassun et al. 2019).

T_{eff} (K)	N	V (mag)	N
6000 – 7000	4305	< 6	31
7000 – 8000	1110	6 – 8	229
8000 – 9000	353	8 – 10	2017
9000 – 10000	155	> 10	3646

After omitting duplicates, 5923 stars were accepted for the analysis. The basic distribution of the temperatures and brightness of the sample stars is shown in Tab. 1.

Since our work started in spring 2021, we downloaded only data observed in Cycle 2, thus, we analysed only data from sectors 14-26 (July 2019-June 2020). SPOC SC and LC data (3403 and 5787 stars, respectively) and QLP LC data (5923 stars) were obtained from the MAST archive using the LIGHTKURVE v2.0 software (Lightkurve Collaboration et al. 2018; Barentsen & Lightkurve Collaboration 2020). LIGHTKURVE v2.0 was also used for merging the data from different sectors. The median time span of the data sets is 352 days for both LC and SC SPOC data, respectively. This means that the vast majority of the studied stars were observed in sectors spread out over the whole cycle 2. Median number of points per data set is 12000 and 170000 for LC and SC data, respectively.

The spatial distribution and number of sectors in which the particular stars were observed are shown in Fig. 1. We note here that the SPOC products were not always available for all the sectors in which the star was observed. For example, there should be data of TIC 229412873 available from 12 sectors from Cycle 2 but there are SPOC data products only for three sectors (all 12 sectors in the QLP routine).

For the forthcoming analysis, we transformed the immediate flux F_i to relative magnitudes Δm_i by using Pogson's equation:

$$\Delta m_i = -2.5 \log \left(\frac{F_i}{F_{\text{mean}}} \right), \quad (1)$$

where F_{mean} is the mean flux of the observations.

We have not applied any additional cleaning or detrending procedure, filtering of the data or outlier removal and simply used the PDCSAP data as they are provided. The modification of the data sets would need individual approach to each of the stars in the sample which is out of scope of this paper.

3.1. Spectroscopic supporting data

To help to better classify the stars, we gathered available low-resolution spectra of 126 of our targets from the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) of the Chinese Academy of Science (Cui et al. 2012; Zhao et al. 2012) and determined their spectral type by using the MKCLASS code (Gray & Corbally 2014). This software is able to recover the spectral type with results that are comparable with the manual classification (e.g., Gray & Corbally 2014).

We also gathered a new high-resolution spectra ($R = \lambda/\Delta\lambda \approx 40000$ at $H\alpha$) to prove the rotational variability via projected rotational velocity of six stars that may be classified as pulsating stars. The stars were observed with the Ondřejov Echelle Spectrograph (OES) mounted on the 2m Perek Telescope, Academy of Sciences, Czech Republic (Kabáth et al. 2020). All the spectra had signal-to-noise ratio (SNR) above 100 near $H\alpha$.

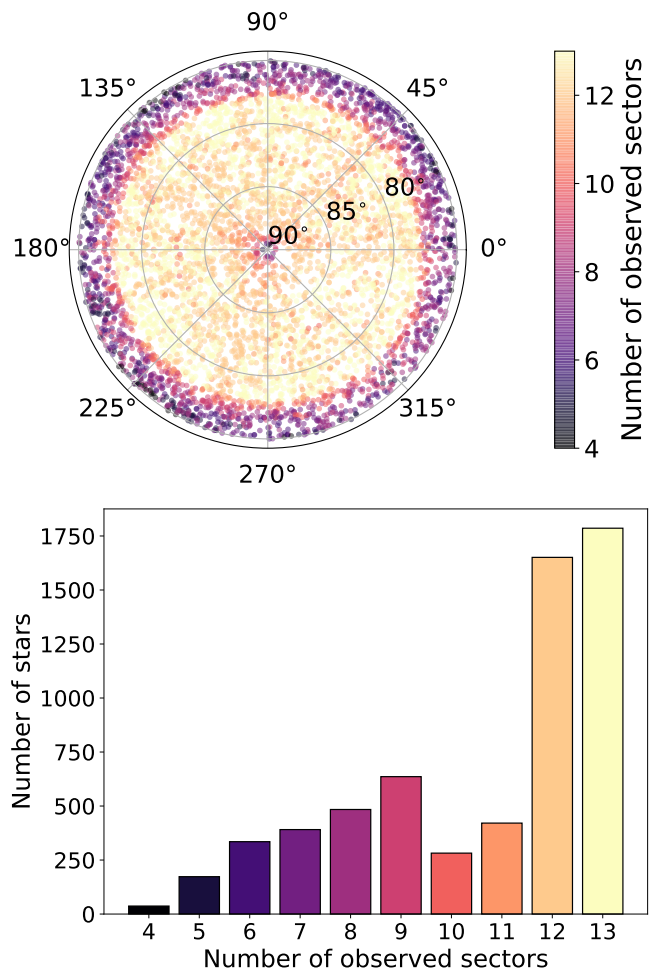


Fig. 1. The position of the investigated stars around the northern ecliptic pole in the ecliptic coordinates (top panel). The color coding shows the number of sectors in which the data were available in the SPOC routine. The bottom panel shows in how many sectors were the data available for how many stars.

The spectra were modelled with the iSpec software (Blanco-Cuaresma et al. 2014; Blanco-Cuaresma 2019). As the input parameters for the fitting with radial transfer code SPECTRUM (Gray & Corbally 1994) and MARCS model atmosphere (Gustafsson et al. 2008), we used the values of T_{eff} and $\log g$ from the TIC catalogue (Stassun et al. 2019) and adjusted them to better fit the spectra if necessary. Subsequently, we fixed these values and left the $v \sin i$ as the free parameter and determined the projected rotational velocity.

4. Identification of variability and data shortcomings

Stellar variability in the space data is usually investigated in the time (light curve) and frequency (Fourier transform of the data, from now on "FT") domains (e.g., Balona 2011; Bradley et al. 2015). We created the FT of the LC and SC SPOC and QLP data³ by using python implementation of the non-uniform fast Fourier transform⁴ that is significantly faster than a classi-

³ In the range of 0-300 and 0-24 c/d for the SC and LC data, respectively.

⁴ <https://github.com/dfm/python-nufft>

cal Lomb-Scargle periodogram (Lomb 1976; Scargle 1982) but gives basically the same results for the TESS data.

The periodic signal with frequency f in the data is usually considered as real if the SNR of the corresponding peak in the frequency spectrum is larger than four (Breger et al. 1993). We define the SNR as the ratio of the amplitude of the peak at a given frequency f and the mean amplitude of the peaks in the vicinity of the peak $f \pm 1$ c/d. This is more conservative approach than to use power-amplitude spectrum or define the SNR as the ration of the amplitude of the peak and the standard deviation of the peaks in the immediate vicinity as is often done (e.g. Balona 2011; De Medeiros et al. 2013). We did not apply any amplitude threshold (as was done, e.g., by Uytterhoeven et al. 2011b; Bradley et al. 2015) because the each target has different noise level.

The basic problems in the identification (and classification of the variability in general) arise from the natural characteristics of the data (noise, sampling, time span of the data, data reduction and detrending) in combination with the variability timescales and amplitudes. We demonstrate these issues in Figures 2 and 3. The data reduced with different routines and with different sampling must naturally be different. As is apparent from the top panel of Fig. 2, the amplitude of the light variations in the LC data have smaller amplitudes averaging out the fast variations.

The QLP routine removes the large-amplitude variations by applying the high-pass filter (the bottom panel of Fig. 2, orange points, Huang et al. 2020a). From the bottom panel of Fig. 2, it is also apparent that residual instrumental and reduction artifacts due to imperfect background subtraction and/or poorly defined aperture might be present in the data (magenta diamonds, SPOC LC data). These artifacts appear more often in the SPOC LC data than in the SPOC SC or QLP data and can cause serious trouble in classification of variability type. In the worst case, the artifacts can lead to a complete wrong classification. QLP routine can even fully remove the variations (Fig. 2, bottom panel). A nice comparison of the available data products and their suitability for the large-amplitude variables investigation, particularly for Cepheids and RR Lyrae stars, observed by the Kepler (Borucki et al. 2010) and TESS missions, can be found in Plachy et al. (2019) and Molnár et al. (2022), respectively.

Figure 3 shows an example of how the frequency spectra for the SPOC data with different sampling can differ. There is a significant peak with $SNR > 4$ in the SC data (shown with black color), while there is no significant peak in the FT of the LC data (yellow points and line). According to the SC data and the peak, TIC 2116199 should be considered as a variable star. However, because the FT of LC data shows no significant peak and there is actually no apparent variability in the light curve, we assume that the possible variation is of artificial nature and classify TIC 2116199 as a non-variable star.

From all the above mentioned reasons, we performed careful individual investigation of all available data sets for each star giving the preference to the SPOC SC data (where available) that seem to be the most reliable. The identification of variability and subsequent classification was performed individually case by case. Further shortcomings of the classification are discussed in Sect. 6.

5. Classification schema and notation

Similarly to the identification of real variations (see Fig. 2 and 3), also the classification based solely on the photometric data can be a difficult task leading to an ambiguous solution. Usually, multi-parametric classification employing periods, light curve

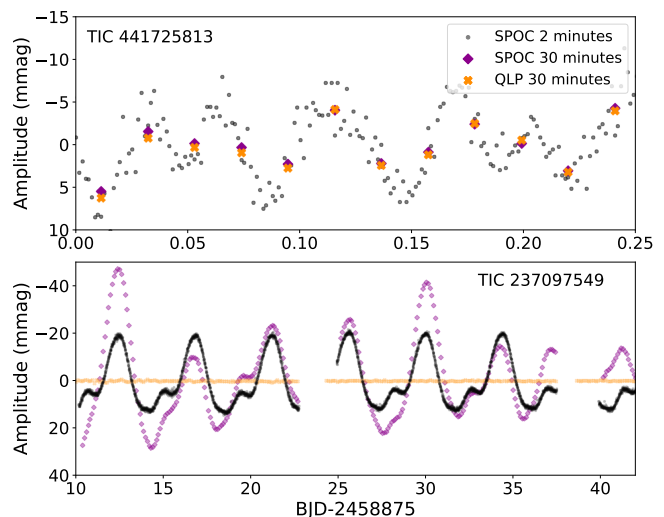


Fig. 2. Figure showing comparison of the data with different sampling obtained with different routines. In low-amplitude short-period variable stars, the LC data from QLP and SPOC data products give similar results but with smaller amplitude (the upper panel). The bottom panel shows that already in stars with amplitudes in the order of tens of millimagnitudes, the long-cadence data can suffer from some instrumental variations (magenta points) and QLP routine fully removed the variability. In both stars, the LC data are less reliable than the SC data.

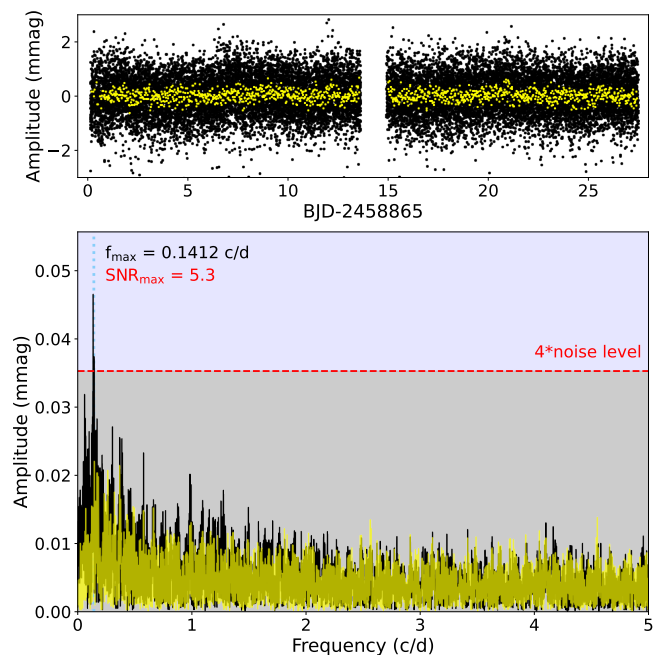


Fig. 3. SPOC data of TIC 2116199 from the sector 14 (top panel) and frequency spectra based on four available sectors with the time span of 352 days (bottom panel). The LC data and the corresponding frequency spectrum are shown with yellow, the SC data and the corresponding frequency spectrum with black. The red dashed horizontal line shows the four times noise level limit, while the vertical dotted blue line shows the most significant frequency.

and frequency spectra characteristics are used (e.g., Uytterhoeven et al. 2011b; Balona et al. 2011; Bradley et al. 2015). Some types of variable stars are easily recognizable on the first look (typically the high-amplitude variables, e.g. eclipsing binaries of Algol type), but in some variability types the classification may even be impossible. For example, light curve of an ellipsoidal

variable can look the same (including periods and amplitudes) as an over-contact eclipsing variable of W UMa type or spotted chemically peculiar star; pulsations can mimic rotation, etc. (see Sect. 6).

For each star, we produced a figure showing the time series data, data phase-folded with the dominant frequencies below and above 5 c/d, a target pixel file with the aperture, and frequency spectra divided to parts below and above 5 c/d (Fig. 4). This frequency limit is a usually accepted value dividing the GDOR and DSCT pulsators (Grigahcène et al. 2010) that have been applied in many studies dealing with the data obtained from space (e.g., Uytterhoeven et al. 2011b; Balona et al. 2011; Bradley et al. 2015). Plots shown in Fig. 4 served as the main decision factors for the classification. If needed, particular stars were investigated more closely.

The basic variability types were adopted from the Variable Stars Index catalogue⁵ (VSX, Watson et al. 2006). The notation is based on the classification system by the General Catalogue of Variable Stars (GCVS, Samus et al. 2009). For the stars that are certainly variable but we were not able to determine the variability type, we used 'VAR'. If there is ambiguity between two or more variability types, we use pipe '|' meaning 'or'. If a star shows a combination of variability types, we give plus '+' sign with the variability type of larger amplitude in the first place.

Because the temperature of the stars in our sample covers a wide range, also the expected mixture of physical mechanisms of variability is very broad. We can expect stars showing signs of pulsations, cool and chemical spots on the surface of the stars, everything complicated by the mixture of these effects, in addition, often accompanied by binarity. Thus, we tried to search for the general characteristics and put emphasis on the explanation of the physical mechanisms of variability standing behind.

We considered finer division to a more specific types only in high-amplitude stars (for example, EA versus EB, RRAB versus RRC, etc.). There were attempts to perform a more delicate classification also in low-amplitude classes of variables. For example, Balona et al. (2011) introduced three subclasses of GDOR stars according to their light-curve shape (symmetric, SYM, and asymmetric, ASYM) and frequency content (multiple modes, MULT). Similarly, Balona (2011) introduced three classes of rotationally variable stars (SPOT – multiperiodic with dominant frequency, SPOTM – clear travelling wave, SPOTV – clear dominant period). Similar notation as for GDOR stars created by Balona et al. (2011) was introduced also for DSCT stars by Bradley et al. (2015). However, we did not perform such fine classification. The reasons are that there can be ambiguity in the variability types. Instead, we decided to build a classification on the assumed physical mechanisms rather than on the look of the light curve (see Sect. 5 and 6). We also did not distinguish between DSCT and SX Phe stars and do not divide DSCT to LADS and HADS classes (Frolov & Irkaev 1984; Petersen & Christensen-Dalsgaard 1996). Similarly, we do not distinguish between low- and high-amplitude GDOR stars (Paunzen et al. 2020).

The variability types and criteria for stars to be classified as those, are listed in Tables 2-4 including light curves and corresponding frequency spectra of the typical examples. The types and results are explored in details in Sections 6 and 7. In Sect. 6, we discuss details and trouble in classification. In Tables 2-4, we do not show the minor variability types identified in our sample. We identified two RRAB/BL stars (RR Lyrae of ab type show-

ing the Blazhko effect)⁶ and one RRC star⁷ accompanied with one RRAB and two RRC candidates that have amplitudes only in range of mmag which is very suspicious. We also found five candidates of roAp stars which show frequencies above 100 c/d.

In Table 5 we provide the identification, classification, frequency of the dominant peak in the FT and the amplitude of the brightness variation. We also give a cross-match of our sample with the VSX catalogue with the distance limit of 20". There are 172 variable stars from our sample in the VSX (version 2022-02-21), while in 10 of the VSX stars we did not find any variation. For the eclipsing binaries, we also give the zero epoch M_0 of the primary eclipse in Table 5.

The amplitude given in Table 5 is a rough visual estimate of the maximum amplitude (from minimum to maximum light) seen in the data. For example, the amplitude of TIC 272749171 shown in Fig. 4 is 70 mmag. This value is only indicative and can be different from the real amplitude of the variations. For example, the data must not contain the extrema of the variations, the light of the object can be contaminated by the light of nearby stars, the amplitude may be decreased by the long cadence in case of fast variations.

6. Ambiguity in classification and other related shortcomings

6.1. Blending

One of the reasons why we give only a rough estimate of the amplitude in Table 5 is that the value can be significantly affected by the stars contaminating the light in the apertures (TESS has spatial resolution of only 21"/px, Ricker et al. 2015)). In extreme case, the star in the sample itself can be stable and the variation can come from a nearby variable star. We did not investigate this issue in detail but we performed a quick analysis concerning stars within our sample. We checked stars that were closer than 10 pixels from each other. Based on the amplitude of the peaks in the frequency spectrum, we decided which star is variable and which not.

Figure 5 shows two examples of blending stars. In the top panel, we can see that the variability comes from the fainter star, TIC 232681382, which has peaks in the FT with higher amplitudes. In the bottom panel, the situation is the opposite: the brighter star (TIC 233545407) is the variable one. In our sample, we identified 29 such couples among stars classified as variable from which 21 pairs show the same FT with different amplitudes. For such cases, we give a comment that the variability is caused by a close companion in the last column in Table 5.

There might be more blends with fainter stars. Detailed inspection of the stars around each object in our sample is out of scope of this paper. Nevertheless, we cross-matched our sample with the GAIA DR2 catalogue (Gaia Collaboration et al. 2018) and identified all stars that are not fainter than 5 mag (in GAIA g filter) than our variable star and are closer than 105" (5 px) to it. We give the number of such stars in the last column of Table 5. This value gives at least a warning about possible blends that can also cause false positive identifications of variable stars. Thus, the reader should seriously take into consideration the possibility of blending.

⁵ <https://www.aavso.org/vsx/index.php?view=about.vartypes>

⁶ saw-tooth light curve shape, harmonics of the basic frequency in FT

⁷ more sinusoidal shape, harmonics of the basic frequency in FT

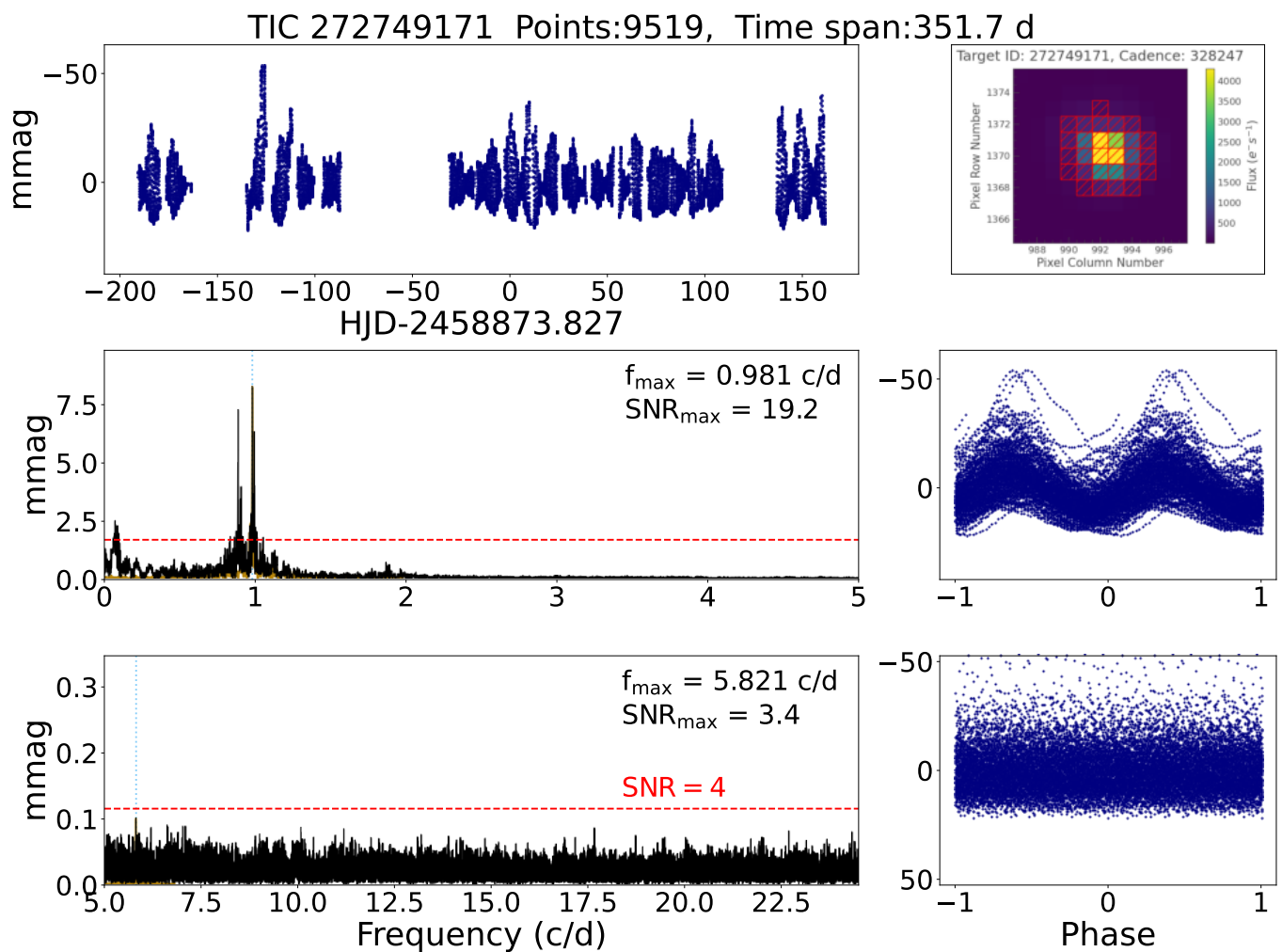


Fig. 4. An example of the figures that have been produced and used for the basic classification of each of the stars in the sample. The upper left panel shows the data, the top right panel shows the target pixel file with the aperture, the middle and bottom panels show the frequency spectra (left) and the data phase folded with the most prominent peaks in the frequency spectra (right).

6.2. Instrumental, data reduction artifacts, semiregular and long-period variations

The data we used is the simple aperture photometry (SAP) processed with the Presearch Data Conditioning (PDC) pipeline (Smith et al. 2012; Stumpe et al. 2014). This pipeline uses co-trending basis vectors to remove systematics such as those resulting from the focus changes, spacecraft pointing jitter, and other stochastic errors, as well as the crowding problems (see e.g., Jenkins et al. 2016; Jenkins & et al. 2020; Kinemuchi et al. 2012). Mostly because of the scattered light and due to improper aperture definition, there might be additional variation present in the data (as already pointed out in Sect. 4) that is not intrinsic to the star. It is not always possible to distinguish between stellar variation and instrumental and reduction artifacts.

Generally, we can expect that the instrumental/reduction artifacts will cause irregular or semi-regular variations with periods longer than 1 day producing groups of low-amplitude peaks with frequencies below 1 c/d in the FT. Typically, artifacts can be mixed up with stellar activity, rotational modulation due to spots, or GDOR type pulsations. From the high risk of instrumental artifacts or misclassification, we conservatively assigned the spurious cases with 'VAR' label although some of the stars could be assigned with a particular variability class. Actually, stars showing similar light curves and FTs as TIC 334678134

and TIC 417734885 (shown in the top row of Table 3) have been often considered as stars showing rotational modulation or stellar activity (e.g., Balona 2011, 2013; Bradley et al. 2015).

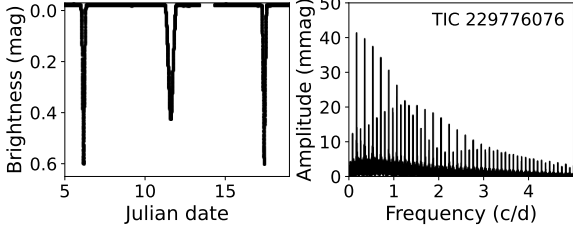
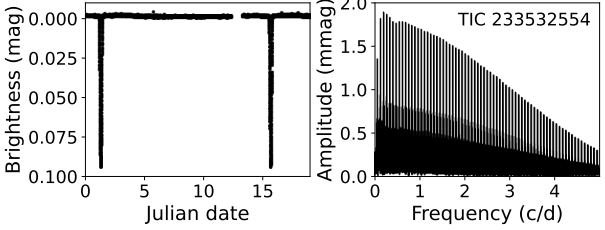
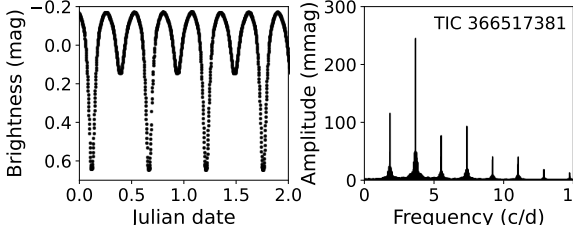
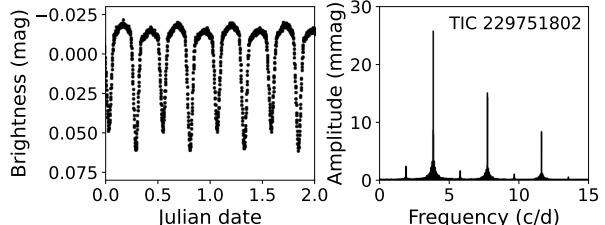
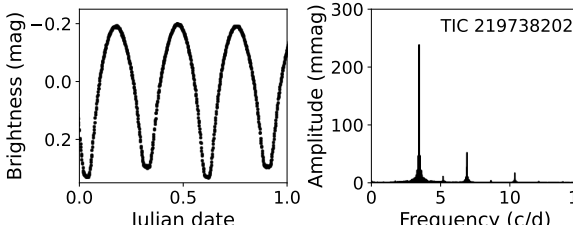
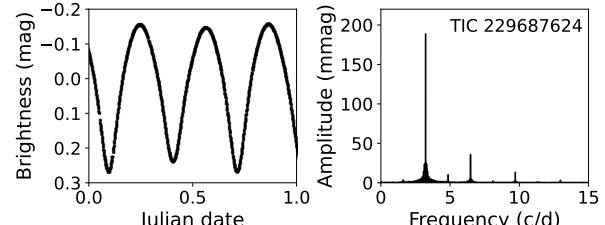
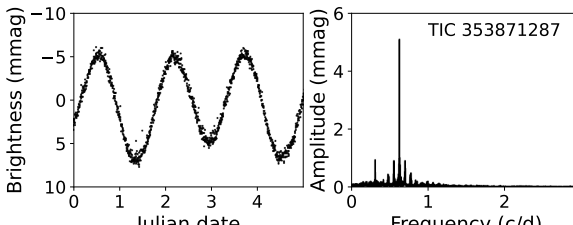
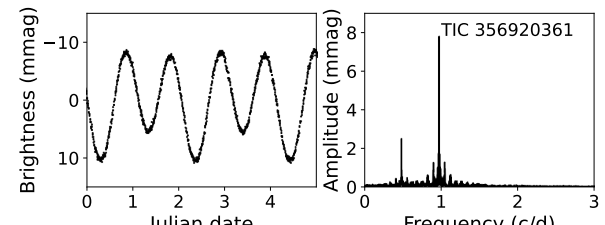
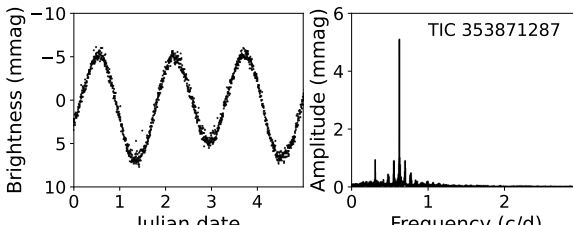
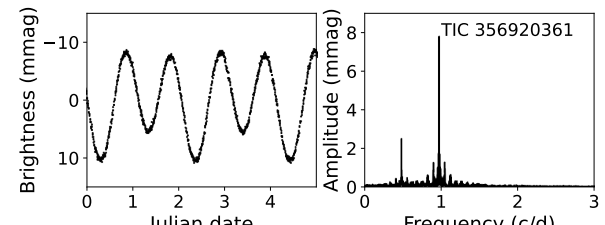
Because our sample stars have temperatures in a broad range we cannot simply omit low-frequency regions (as is often done) because there might be signs of slow rotators with periods in order of days. For example, (Uytterhoeven et al. 2011b) omitted frequencies below 0.5 c/d, Bradley et al. (2015) and Balona (2011) did not consider frequencies below 0.2 c/d.

6.3. Pulsating variable stars

There are three types of pulsators in the region of A-F stars. First of them are DSCT stars (p -mode pulsators) that are easily recognizable and the class is well defined because basically any variability with frequencies above 5 c/d is caused by the pulsations of DSCT type (for the examples see the figures in Table 3). There are also Population II stars that show similar behaviour as DSCT stars (SX Phe). However, we do not distinguish between these two types.

Regarding the FT, the upper limit of 100 c/d differentiates DSCTs from the second pulsating type, roAp stars (Kurtz 1982). However, the upper limit is not firmly set and depends on a particular author (e.g. Balona 2022, used 60 c/d). The mechanism

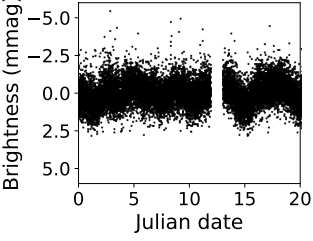
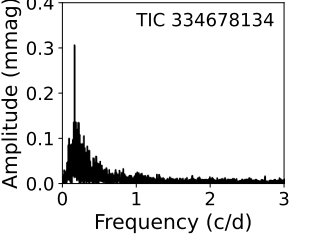
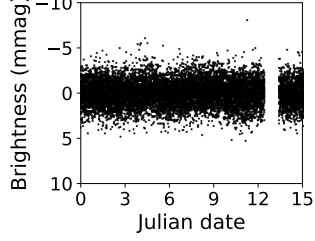
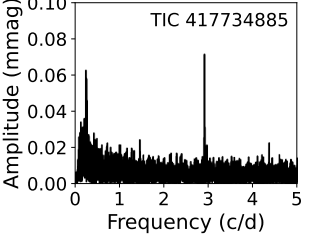
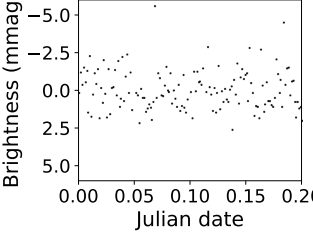
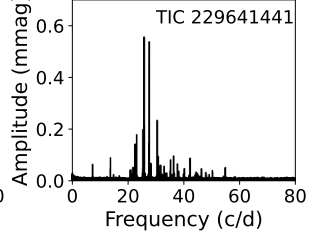
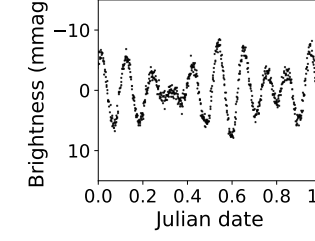
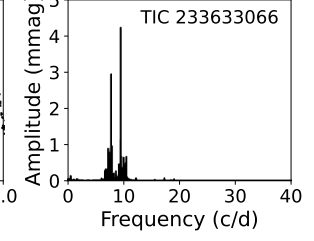
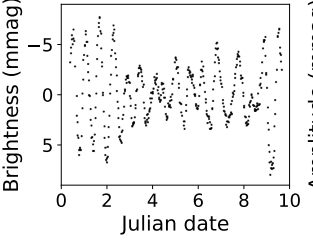
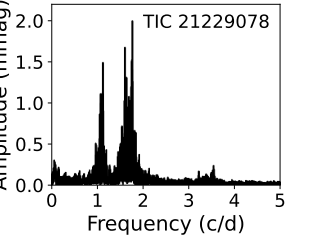
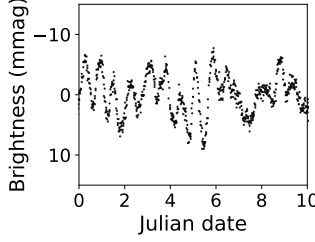
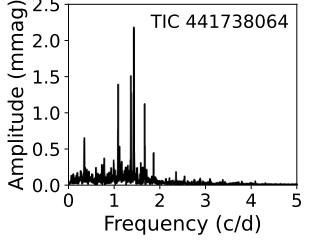
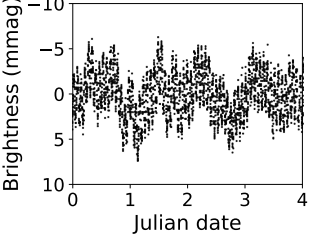
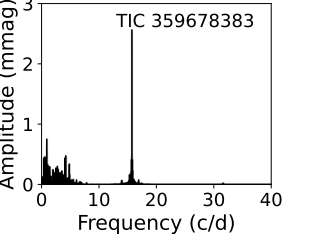
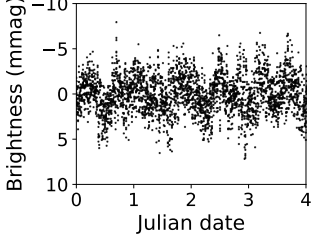
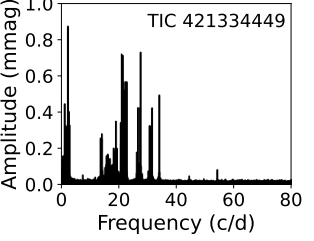
Table 2. Typical examples of the variability types caused by binarity of the stars. The notation is in the first column 'Type', description of the characteristic features present in the light curve is in the second column, characteristics features in the FT are described in the third column. The assumed physical origin of the brightness variations is in the fourth column. For each variability type we show parts of the light curves reflecting the basic variability for two example stars including the FTs of the full available data sets. The Julian date is arbitrarily shifted. There are no examples of EP shown because they are basically low-amplitude EA type. Note the different scales of the vertical axes.

Type	Light curve	Frequency spectrum	Physical origin
EA	constant light in maximum, deep sharp minima 	lots of well defined harmonics of the basic frequency with slowly decreasing amplitudes 	eclipses in binary system with detached components
EP	constant light in maximum, shallow eclipses with the same depth (typically with amplitudes < 10 mmag) 	lots of well defined harmonics of the basic frequency with similar amplitudes 	transits of an exoplanet
EB	variation in maximum light, well defined minima with (generally) different depths 	lots of well defined harmonics of the basic frequency with decreasing amplitude 	eclipses in binary system with deformed component(s)
EW	smooth brightness variation, flat bottom of eclipse(s) may be present, amplitudes > 100 mmag 	well defined harmonics of the basic frequency with quickly decreasing amplitudes towards higher frequencies 	eclipses in binary system with components filling their Roche lobes or sharing common atmosphere
ELL	smooth brightness variation, strictly symmetric and repeating light curve without sharp features, maxima have the same brightness 	one or two dominant peaks at harmonics ($f_1 = 2f_2$), additional low-amplitude harmonics may be present, amplitudes < 100 mmag 	non-eclipsing binary system with tidally deformed components

responsible for the rapid oscillations is not yet known. Currently the most accepted is the opacity mechanism in the hydrogen ionisation layer where the convection is suppressed by the magnetic field (Balmforth et al. 2001).

The last type of pulsations occurring among A-F type stars is pulsations of GDOR type. The g-mode pulsations are believed to be excited by the convective flux blocking mechanism (Guzik et al. 2000; Dupret et al. 2005). Frequencies observed in GDOR

Table 3. Typical examples of the variability types assumed to be caused by stellar pulsations. The columns are the same as in Table 2.

Type	Light curve	Frequency spectrum	Physical origin
VAR	weak or no signs of variability (low amplitude) and/or ambiguity in classification	single peak (with frequency usually below 1 c/d) and/or peaks with unclear nature, peaks with low SNR	unknown origin, possible stellar activity or instrumental artifacts
			
DSCT	(ir)regular fast variations, beating, bumps, interference	two and more independent peaks above 5 c/d	p-mode pulsations
			
GDOR	(ir)regular variations, beating, bumps, interference, sharp variations	two and more independent peaks below 5 c/d, peaks are usually in groups, well-defined single peaks are not harmonics, groups of peaks can be close to the positions of their harmonics	g-mode pulsations
			
GDOR+DSCT; DSCT+GDOR	(ir)regular variations, beating, bumps, interference, sharp variations	two and more independent peaks below and above 5 c/d	p- and g-mode pulsations
			

pulsators are usually between 0.3 and 3 c/d (Kaye et al. 1999; Henry et al. 2011) but can also be above 5 c/d although with small amplitudes (Grigahcène et al. 2010). Similarly, the DSCT pulsations can have frequencies below 5 c/d but with small amplitudes (Grigahcène et al. 2010). This can lead to a misclassification between GDOR and DSCT stars in a small fraction of stars. We classified a star as a GDOR if it shows two and more peaks with frequencies below 5 c/d that are not harmonics of each other. Peaks in FT of GDOR stars often create groups.

Such pattern is characteristic for a significant portion of GDOR stars (see the examples in Table 3 and Fig. A.1). We cannot exclude the possibility that in clear GDOR stars some of the peaks can be caused by spots and rotation.

Significant part of A-F stars show both GDOR and DSCT pulsations (see the examples in Table 3 and in Fig. A.2), some of them known prior to space missions (e.g., Henry & Fekel 2005; Handler 2009). Such stars are called hybrids. Balona (2014) found that basically all DSCT stars show low-frequency peaks

Table 4. Typical examples of the variability types caused by rotation of a single star. The columns are the same as in Table 2. For the type 'ROT' we show the phase curves because the variations are better visible.

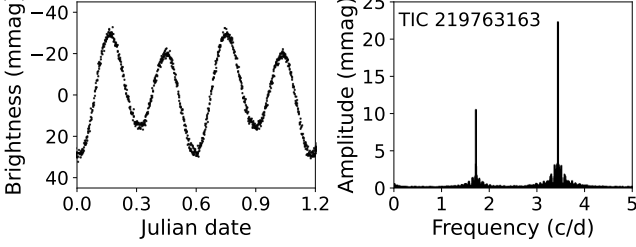
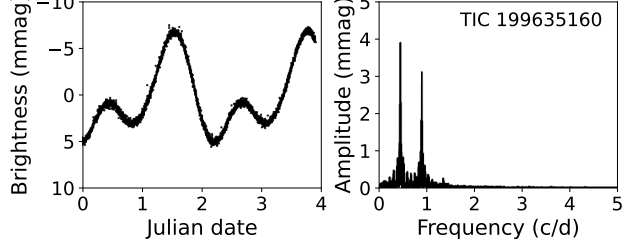
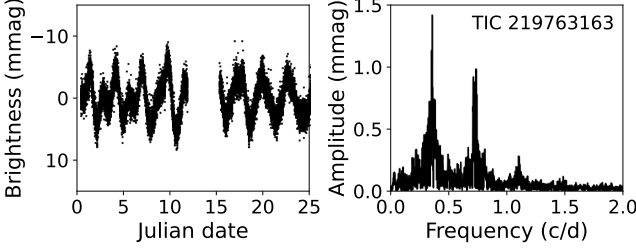
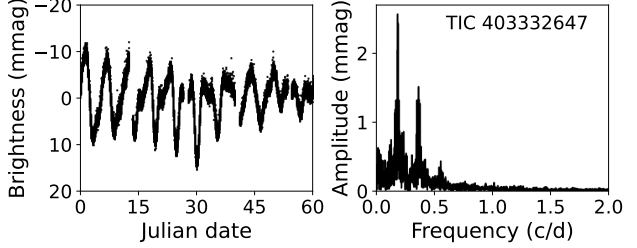
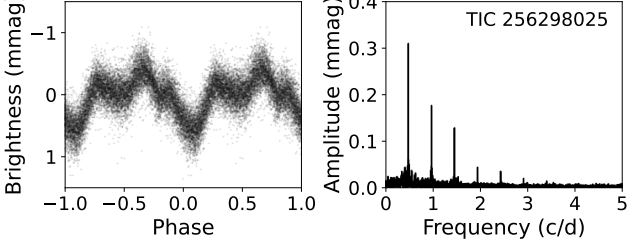
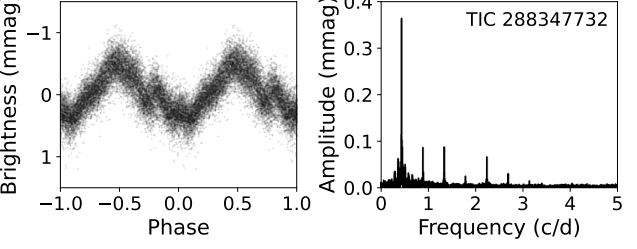
Type	Light curve	Frequency spectrum	Physical origin
ROTM	strictly repeating pattern, smooth variation without sharp features, maxima and minima generally different, superposition of two waves	one or two dominant peaks that are harmonics of the basic rotational frequency ($f_2 = 2f_1$), low-amplitude harmonics of f_1 may be present	rotation of a star with chemical spots
			
ROTS	irregular variations superimposed on a basic periodic pattern	groups of (unresolved) peaks at positions close to harmonics of the strongest peak	rotation of a star with migrating (and forming/disappearing) spots, activity similar to our Sun, possible instrumental/data reduction artifacts
			
ROT	repeating stable features	harmonics of the strongest frequency	likely some phenomenon related to the rotation of the star
			

Table 5. A part of the table with the designation in the TIC catalogue (the first column), positions (columns 'RA' and 'DEC'), classification of the stars ('TYPE'), Spectral type based on the LAMOST spectra, dominant frequency (f), zero epoch ' M_0 ' (for eclipsing binaries), amplitude of the brightness variation (ΔT), the designation and classification in the VSX catalogue (VSX and VSX type) of the sample stars. The column 'Blend' gives a TIC number of the blending star that is variable, while the last column ' N_{stars} ' gives the number of stars that are closer than 5 pixels from the object and the difference between object and the blending star is less than 5 mag. The full table is available online.

TIC	RA (deg)	DEC (deg)	TYPE	Sp. type	f (c/d)	M_0	ΔT (mmag)	VSX	VSX type	Blend	N_{stars}
21002602	272.7745522	53.4938379	ROTS		0.376		4.0				0
21018571	273.0771419	52.66231947	ELL		0.993		2.0				0
21031802	273.3209365	52.41759483	DSCT		9.391		10.0				3
...

and are, therefore, hybrids although some exceptions exist (Bowman 2017). We marked a star as a hybrid when at least two significant peaks ($SNR > 4$) with frequencies below and above 5 c/d are present. This is somewhat weaker criterion than has been used, for example, by Uytterhoeven et al. (2011b) and Bradley et al. (2015) who used an amplitude threshold and required that

the amplitudes of the peaks in GDOR and DSCT regimes are similar (factor of 5-7). There is a risk that some of the frequencies can actually be a combination of other frequencies. This would lead to a wrong hybrid classification. Further, in rapidly rotating GDOR stars, some of the peaks above 5 c/d can actually be g modes shifted to higher frequencies due to rotation

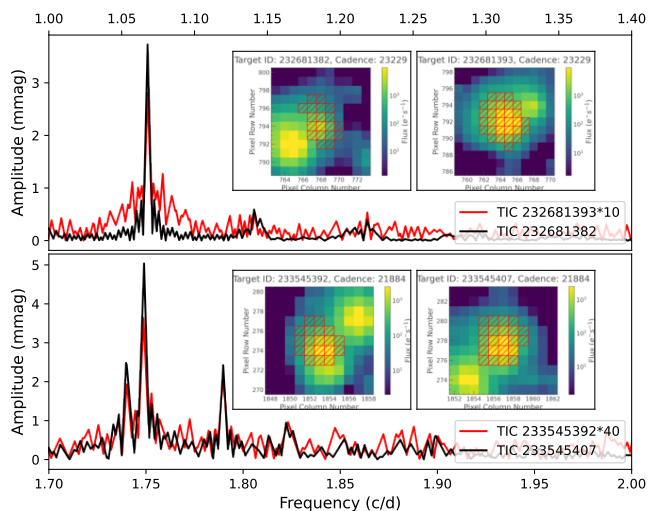


Fig. 5. The frequency spectra of two couples of blending stars. The apertures are shown in the insets. The red spectra correspond to non-variable stars contaminated by the nearby variables. The amplitudes of the peaks of non-variable blends are multiplied for a better visibility by 10 and 40, respectively.

(Bouabid et al. 2013). However, we assume that these issues would be present only in a small fraction of the stars. Because a detailed individual frequency analysis of the data is out of scope of this paper, we have not considered these effects in our classification.

More of a serious problem for the classification and identification of the real highest peak in the FT is the sub-Nyquist artefacts. In case of perfectly sampled data with a 30-minute cadence, the value of the Nyquist frequency would be $f_{\text{Nyquist}} = 24 \text{ c/d}$. Frequencies of some of the pulsation modes of DSCT stars can lie above this limit. Frequency f_{Real} in range of $24 < f_{\text{Real}} < 48 \text{ c/d}$ will be reflected to a position $f_{\text{Reflected}} = 2f_{\text{Nyquist}} - f_{\text{Real}} = 48 - f_{\text{Real}}$. DSCT frequencies close to $2f_{\text{Nyquist}}$ will be reflected to a low-frequency region, where they possibly could mimic GDOR and ROTS frequencies. However, such frequencies will be heavily dumped in amplitude since the corresponding period of the pulsation cycle is comparable with the exposure time of the LC data (Balona 2014). We performed a simple test and compared the FT of LC and SC data and found out that about half of the GDOR candidates show a peak with higher amplitude close to $2f_{\text{Nyquist}}$ than close to 0 c/d in the LC data. However, the SC data showed in all cases that the frequencies below 5 c/d are the real ones and that there is no danger that the GDOR stars are confused with DSCT stars due to Nyquist reflections.

Concerning the DSCT stars, the SC data secure that the DSCT frequencies are identified properly and the classification is correct. In the LC data, the perfect sampling is disrupted by the downlink of the data, which causes that the observations do not start exactly after $n \times 30$ minutes (n is an integer). This detuning is boosted in the TESS CVZ by multiple gaps (downlinks) and should allow for a reliable identification of the real pulsation frequencies of DSCT stars even if they are higher than f_{Nyquist} (Murphy 2015). However, the identification is not always perfect.

For stars classified as DSCT based on the LC data, we performed the FT analysis again in the range $0\text{--}60 \text{ c/d}$ to retrieve possible frequencies above 24 c/d . To check how reliable such frequencies are in the LC data, we compared the results of 16% of all DSCT that have both LC and SC data (examples are shown

in Fig. 6). The frequency with the highest amplitude identified in the SC data was successfully retrieved only in 50% of the test cases in their LC data (see panel (D) in Fig. 6). Thus, the DSCT frequencies above 24 c/d in Table 5 may be wrong in 50% of stars that do not have SC data. However, the classification as DSCT remains correct. Further, we noticed that the frequency with the highest amplitude in the FT of SC data (that we expect to be the real dominant frequency) might not necessarily be the dominant frequency in the FT of LC data (panels (A)–(C) in Fig. 6). This is probably the result of a different sampling and smaller amplitude of the fast light variations in LC data.

6.4. Rotationally variable stars

Rotation is a fairly stable phenomenon. Thus, in rotating stars, we expect regular pattern in form of harmonics (kf_0) of the basic rotation frequency (f_0). The rotational variability can be induced by orbital motion of tidally deformed components of a non-eclipsing stars (ELL type, the last row in Table 2) or by spots on the surface of a single rotating star (Table 4). Among A-F type stars, these spots are supposed to form via gravitational settling of light elements (He) and radiative levitation of heavy and earth-rare elements (e.g., Si, Sr, Cr, Eu,) forming a class of chemically peculiar stars (Michaud 1970; Preston 1974). If a strong dipole magnetic field (inclined with respect to the rotational axis) is present, the spots formed usually around the magnetic poles can produce a rotational variability (Stibbs 1950; Kochukhov 2011).

The rotation periods of the spotted stars are quite long – mostly in the order of days (Sikora et al. 2019) to hundreds of days or even years (Mathys 2017; Mathys et al. 2020). With one-year-long time base (at best), we are confined maximally to tens-of-days-long periods. The light curves of magnetic chemically peculiar stars have mostly sinusoidal or doubly sinusoidal light curves (Jagelka et al. 2019). We assign stars with stable light curves showing two (or more) harmonics in the FT as ROTM (meaning magnetic rotators, Figures in the top row of Table 4) since we assume that the variation is caused by stable chemical spots that require strong magnetic fields⁸. Possible additional long-term variations are interpreted as instrumental/reduction artefacts (see Fig. 2). We do not assign sinusoidal variation (one significant peak in FT) as ROTM since it cannot be unambiguously distinguished from ELL type and classify such stars as ROTM|ELL (see subsection 6.5).

As shown by many authors (e.g., Balona 2011, 2013; Hümmelich et al. 2018; Sikora et al. 2019), A-F stars can also show more complex light curves including the variation in amplitude. The variation can be highly irregular and can cause variation from cycle to cycle (see Figures in the second row of Table 4 and also figures in e.g. Balona 2013; De Medeiros et al. 2013; Sikora et al. 2019; Trust et al. 2020). These variations are usually attributed to rotation and activity of a star with spots that can form and disappear and migrate due to differential rotation (Solar-like activity, e.g., Balona 2011; Debosscher et al. 2011). However, one should be aware of mixing the artifacts with real variations (see Fig. 2).

Sikora et al. (2020) studied projected rotational velocities of 44 A- and late B-type stars showing rotational modulation in their light curves and found out that more than 10% but likely less than 30% of main sequence A-type stars show this type of variability. This is surprising since stellar activity of this type is

⁸ Jagelka et al. (2019) showed that the role of the magnetic field in forming the chemical spots may not be as important as is formerly supposed.

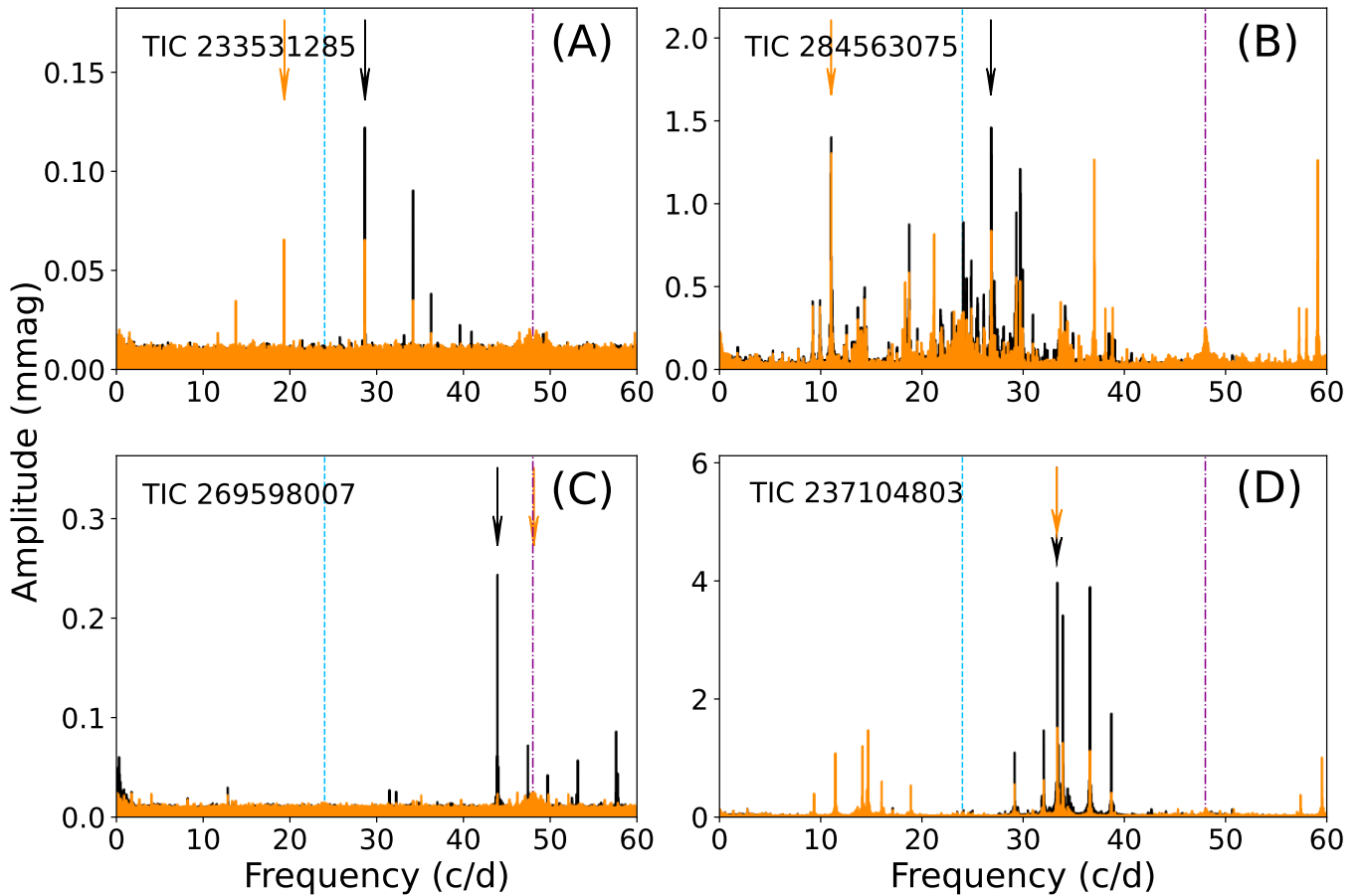


Fig. 6. Comparison of the FT based on the LC (orange) and SC (black) data of four DSCT stars. Frequencies with the highest amplitudes in the LC and SC data are marked with arrows of corresponding colour. The Nyquist frequency and its harmonic at $2f_{\text{Nyquist}}$ are shown with the vertical light blue and magenta lines, respectively. Panel (A) shows the example when the Nyquist reflection of the highest peak would be detected in LC data, panel (B) shows the situation when the peak with the second highest amplitude would be the highest in the LC data, panel (C) illustrates situation when almost no variation is seen in the LC data and the identification completely failed in LC data. Panel (D) shows an example when the proper peak would be identified also in LC data.

not expected in hot stars without large convective envelopes. We assign stars showing semiregular variations producing groups of (un)resolved peaks at positions of harmonics in the FT as ROTs – rotators of Solar type (Figures in the second row of Table 4 and Fig. A.3). The groups of peaks are assumed to be formed due to differential rotation.

Usually, authors assume that also semiregular variations with small amplitude and variations producing one group of peaks (or one single peak) are signs of rotation or activity (e.g. Balona 2011; Uytterhoeven et al. 2011b; Bradley et al. 2015). We are more conservative and assign such stars as VAR (see also Section 6.2).

Because there are lots of stars that show regular periodic pattern in the light curve that transforms into harmonics in the FT, we define the last type of rotational variability that is labelled as ROT (the last row in Table 4, Fig. A.3). The nature of these variations is, however, unclear. The origin can be expected in stable spots or some co-rotating structures governed by high-order magnetic multipoles, as suggested by Mikulášek et al. (2020) and Krtićka et al. (2022) for the hot chemically peculiar stars. However, more likely, these stars are a subgroup of GDOR stars (see Sect. 7).

6.5. Spotted stars or non-eclipsing binaries?

Without spectroscopic observations, based purely on single-passband photometry, there might be ambiguity between ROTM and ELL. In principle, the light variation of a spotted star (the top right-hand panel and red crosses in the middle panel of Fig. 7) can be equally described assuming gravity darkening caused by the tidal deformation of the components of a non-eclipsing system (the top left-hand panel and continuous line in the middle panel of Fig. 7). In addition, the amplitudes of the variations can be similar, as well as periods and FT.

From the geometry, ELL stars must reach the same brightness in maximum light twice a period. However, the same variation can be reproduced assuming two spots on the opposite sides of a star (middle panel of Fig. 7). Thus, this is not a decisive criterion for ELLs. On the other hand, different maximum light typical for ROTM stars can be easily modelled assuming one spot on one of the components of a non-eclipsing binary system. Thus, again, different height of maxima should not be taken as the decisive criterion between ROTM and ELL types but only as a hint. In addition, there can be artifacts causing deformation of the light curve making the correct classification more difficult (Fig. 2).

The bottom panel of Fig. 7 shows IP Dra, a star that was spectroscopically proven to be a binary system (Kjurkchieva &

Marchev 2014). IP Dra is a nice example demonstrating the ambiguity of ROTM and ELL stars and the need of spectroscopic observations for the reliable classification.

It was shown by Morris (1985) and Beech (1985) that if the light curve of ELL variables is described by the sum of sine and cosine functions ($m = A_0 + \sum_{i=1}^N A_i \cos(i\Theta) + \sum_{i=1}^N B_i \sin(i\Theta)$, Θ being phase, A_i and B_i amplitudes, A_0 zero term), the term with the highest amplitude is $\cos(2\Theta)$. This criterion is sometimes used as a support for the assumption of the ellipsoidal variability (e.g., Dal & Sipahi 2013; Li & Liu 2021). The light curve shown in Fig. 7 also shows dominant $\cos(2\Theta)$. Since the dependence can be explained also with spots, the criterion with dominant $\cos(2\Theta)$ is not sufficient for assigning the star as ELL.

Stable chemical spots and rotational modulation are usually observed in hot stars and only exceptionally occur among stars with $T_{\text{eff}} < 7000$ K (Renson & Manfroid 2009a; Hümmerich et al. 2018; Renson & Manfroid 2009b). In addition, the amplitude of the brightness variations usually decreases towards longer wavelengths (e.g., Krtićka et al. 2007, 2015; Prvák et al. 2015). Therefore, we expect only negligible incidence rate of ROTM type among stars with temperatures below 7000 K and assign variations similar to those shown in Table 2 and Fig. 7 as ELL. Stars hotter than 7000 K showing rotational modulation with constant maximum brightness we assign as ROTM|ELL because of the ambiguity between these two types.

6.6. Pulsations or rotation?

To our best knowledge, there are no clear and strict criteria how to distinguish between rotation and pulsations based purely on the photometric data. The issue with discriminating between pulsations and rotation was already pointed out by many studies. For example, De Medeiros et al. (2013) claimed that a better selection of rotating variables can only be made using spectroscopic observations, Balona et al. (2011) pointed out that irregular light curves can be attributed to slowly rotating stars and that the frequencies of the GDOR stars showing symmetric light curves or obvious beating are comparable to rotation frequencies. Actually, most of the studies dealing with the stellar classification based on the space data warn about the possible misclassification between pulsating stars and stars showing rotational variability (e.g. Uytterhoeven et al. 2011b; Balona 2011).

The typical rotational frequencies calculated from the median projected rotational velocity $v \sin i$ and median radius R for A-F stars are between 0.5 and 0.75 c/d (Royer et al. 2007). However, the rotation frequencies can be as high as the critical rotational velocity that corresponds to about 3 – 3.7 c/d in the fastest main sequence A-type stars (Sikora et al. 2019). Thus, there is a strong overlap for rotational variability and pulsations in the FT.

We performed a very simple test inspired by Sikora et al. (2020). We selected six bright examples of ROT, ROTs and GDOR stars and gathered spectra with the OES echelle spectrograph mounted at the Perek 2m telescope in Ondřejov, Czech Republic (see Sect. 3.1). We modelled the spectra using iSpec and measured the $v \sin i$ (see Sect. 3.1). We calculated the bottom limit of the rotational frequency ($v \sin i \leq v_{\text{equatorial}}$) by employing radii of the stars from the TIC catalogue (Stassun et al. 2019). The results are shown in Fig. 8.

Apparently, the measured frequencies agree well with the frequencies detected in the FT of the photometric data of the ROTs stars, while for GDOR and ROT stars the frequencies do not match well. However, the calculated frequencies shown with vertical dashed lines in Fig. 8 are only lower limits. It is possible that some of the peaks shown in the left panels of Fig. 8

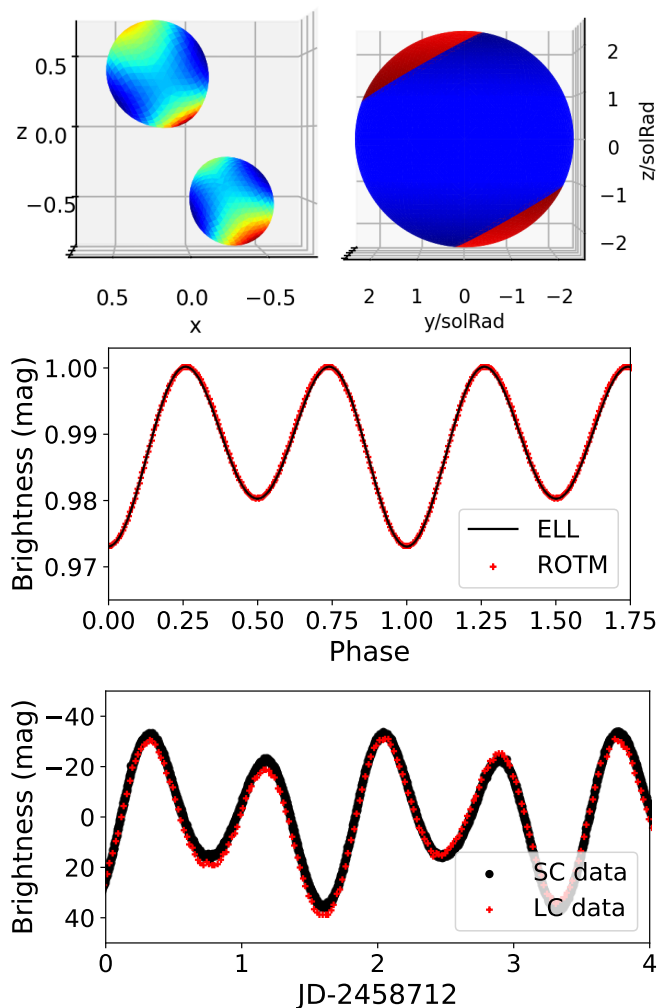


Fig. 7. The generated light curve (middle panel) assuming non-eclipsing binary star with tidally deformed components (ELL, top left panel, black line in the middle panel) and spotted star (ROTM, top right-hand panel, red crosses in the middle panel). An example of the light curve of a spectroscopically confirmed ELL star IP Dra that would rather be classified as ROTM. The models were generated using ELISA (Čokina et al. 2021).

can be addressed with inclined rotation axis and rotation. Thus, this test alone is not a proof that the variation in stars producing (un)resolved peaks at their harmonic positions in the FT is caused by rotation. It is only a strong support for this explanation. In addition, rotation of a star can shift the pulsation frequencies. An example how difficult the correct classification of such stars can be was published by Uytterhoeven et al. (2011a). They found out that variations of HD 171834, that produce unresolved peaks at the harmonic positions in the FT, are rather caused by rotation than pulsations.

It is likely that there remain spurious cases in our sample that would need detailed investigation including spectroscopic observations. TIC 237218644 (top left panel of Fig. 9) would be classified as ROTs according to our methodology but the temperature of 9087 ± 204 K (Stassun et al. 2019) suggests that the origin of the variations is rather in pulsations than in rotation since at such high temperatures stellar activity linked with convection is not expected. There might also be uncertainty in temperature. Due to all these issues, we classify TIC 237218644 as VAR. The remaining panels of Fig. 9 contain stars that show

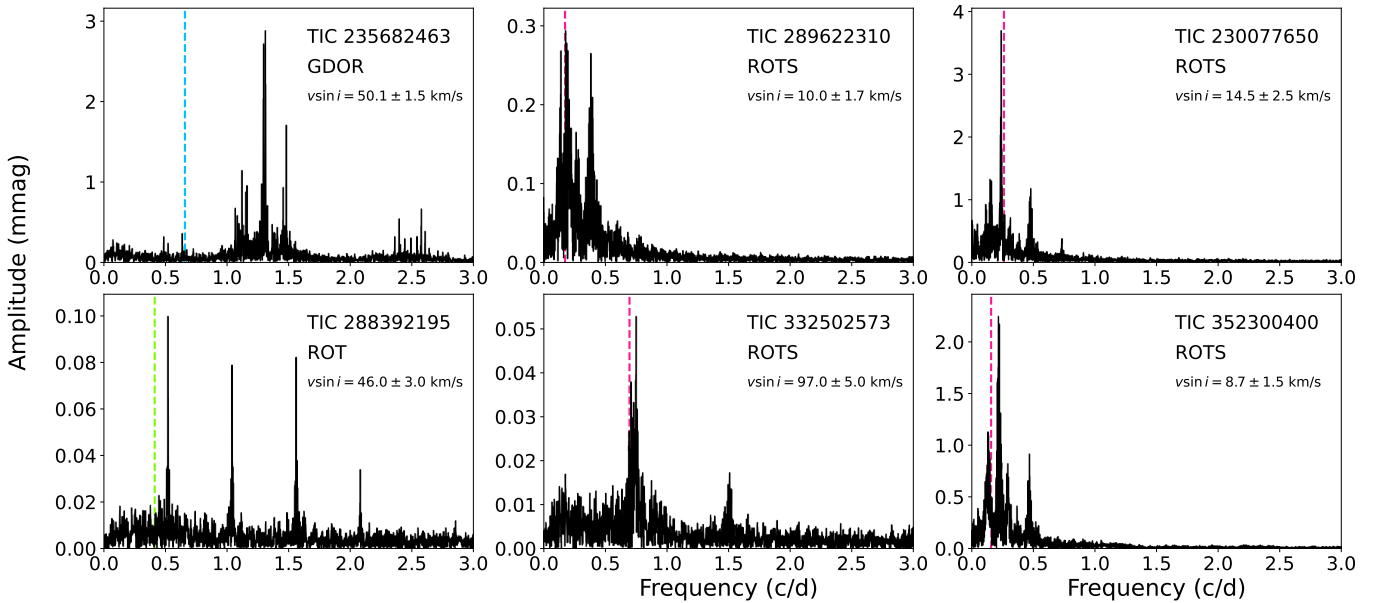


Fig. 8. Examples of FT of GDOR (top left panel), ROT (bottom left panel) and ROTS stars (middle and right panels) showing also position of frequencies calculated from observed $v \sin i$ and catalogue radii of the stars (vertical colour lines). It is apparent that the calculated frequency corresponds well with the observed peaks in the FT of ROTS stars.

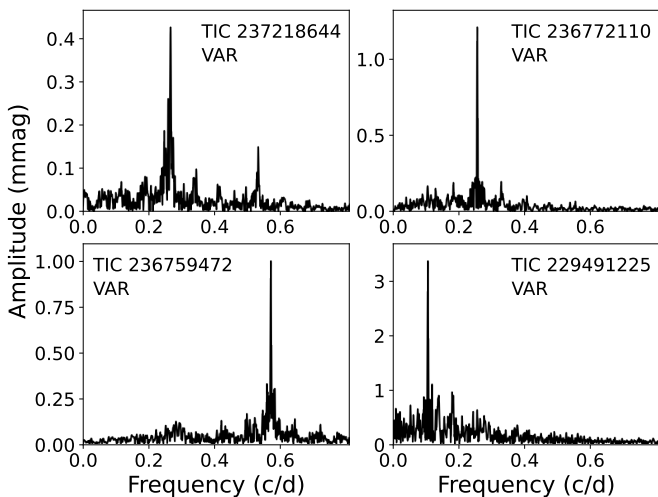


Fig. 9. Examples of frequency spectra of stars with ambiguous classification and, therefore, conservatively classified as VAR. See the text for details.

only one significant peak in the FT. These stars could possibly be classified as ROTS but also as GDOR, ELL or ROTM types. We conservatively classify such stars as VAR.

7. Results and discussion

We identified 3025 stars (out of 5923 in our sample) that show some brightness variations. From these stars, we were able to assign 1813 stars (60%) with a certain variability type. The numbers of stars in particular classes are shown in Fig. 10. The most numerous are GDOR and DSCT classes and their hybrids (together 64.9% of the variable stars). This is in excellent agreement with Uytterhoeven et al. (2011b) who found 63% of stars to show oscillations. In the 'Uncertain' class, there are 34 stars with ambiguous classification with two equally probable types, for example ELL|ROTM, EA|EP, etc. It was not possible to reli-

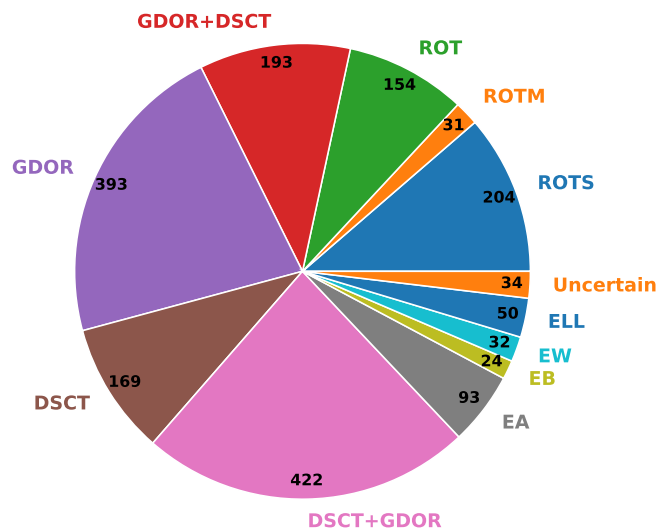


Fig. 10. Numbers of stars in particular variability classes.

ably classify the rest of the variable stars, marked as VAR (1212 stars, see Sect. 6). These are not shown in Fig. 10). In addition to the numbers given in Fig. 10, we identified 6 RR Lyrae stars (1 RRAB, 2 RRAB/BL, 3 RRC) and 7 heart-beat (HB) stars. In five stars we detected frequencies in the roAp range. However, it is not clear whether these are not combination frequencies. Not counting GDOR and DSCT hybrids, 50 stars show a combination of variability types, for example, EA+DSCT, GDOR+HB, etc.

Plotting all the stars in the Hertzsprung-Russell diagram⁹ (HRD, Fig. 11) show some (expected) clumping. The vast majority of GDOR stars is located in a narrow part of the HRD

⁹ Temperatures are taken from Stassun et al. (2019), luminosity of the stars calculated from temperatures and radii from Stassun et al. (2019)

well within the theoretical instability strip (IS) by (Dupret et al. 2005), as shown in the left panel of Fig. 11. The distribution of GDOR stars has maximum at around 7000 K and mean luminosity at about $0.8 L_{\odot}$ (Fig. 12). GDOR stars located outside the IS above approximately 7500 K are uniformly spread over the whole temperature range. Different behaviour of stars in and out of the IS suggests that the hot stars marked as GDOR outside of IS are not of the same type although the nature of the variability is likely in the *g*-mode pulsations.

The temperature distribution of DSCT, DSCT+GDOR hybrids is similar, although DSCT+GDOR hybrids are of about 200 K hotter in average. GDOR+DSCT hybrids have preferentially lower temperatures than their DSCT-dominant counterparts but have the same average temperature as DSCT stars (see Fig. 12). There are a few GDOR, DSCT and hybrid stars with an unexpectedly low temperature. We checked them and would all of them classify as they are (see Fig. A.4). The unexpected behaviour at low temperatures might signalize contamination of the light by nearby stars or less reliable temperatures although the error bars are similar to other stars in our sample. The groups of the rotating variables are well separated in the HRD. In addition, they have different temperature distribution. The ROTS stars (11.3 %) dominate the low-temperature part of the HRD, which can be naturally expected as the variations are supposed to be caused by the spots of Solar type. The ROTM stars (1.7 %) are well spread out over the whole temperature range above 7000 K.

ROT stars (8.5 %) are almost exclusively located near and within the cool edge of the GDOR instability strip. This hints that the observed brightness variations are likely connected with pulsations rather than with rotation. Or, by their combination. ROT stars can, thus, be a new subclass of GDOR stars. The GDOR stars have average temperature 7043 K and frequency 1.358 c/d, while ROT stars have the mean temperature of 6777 K and frequency 0.578 c/d. The mean amplitude is significantly lower for ROT stars (1.5 mmag) than for GDOR stars (9.8 mmag).

Our classification is in a very good agreement with the VSX classification. There are, of course, small differences but the variability types we provide are more specific or the same as in the VSX (with only a few exceptions). We applied our classification schema to three of the previous studies dealing with the classification of variable stars based on the space data (Uytterhoeven et al. 2011b; Balona 2013; Bradley et al. 2015) to see the differences in the classification paying special attention to stars with frequencies below 5 c/d where the ambiguity between pulsation and rotation can emerge (see Sect 6.6). We downloaded the *Kepler* data of the stars with Lightkurve and performed the analysis exactly in the same way as for the stars in our sample.

Among 87 stars classified by Uytterhoeven et al. (2011b) as GDOR we found only 4 stars that we would classify as ROTS and two stars that would be classified as VAR. Thus, the agreement is excellent. However, in one third of stars classified by them as rotation/activity, we found that they are actually GDOR stars or hybrids (see examples in the four upper left-hand panels of Fig. 13). This is significant discrepancy. In 25 % of stars classified as rotational variables by Balona (2013)¹⁰ we found GDOR variability (examples are shown in the four upper right-hand panels of Fig. 13) but we found perfect agreement in all 9 stars classified by Balona (2013) as GDOR.

The worst agreement with our classification would be with the classification by Bradley et al. (2015). From their sample of 195 GDOR stars we would classify 9 as non-variable stars, 39

as VAR, 29 as ROTS, 6 as ROT, 2 as ROTM/ELL and one clear RR Lyrae (four bottom left panels of Fig. 13). This means that we would classify 44 % of stars marked by Bradley et al. (2015) as GDOR with different variability class. We also checked 551 stars classified by Bradley et al. (2015) as rotating variables. We would classify 403 of them (73 %) as VAR or non-variables although the variability of the majority of these stars can be possibly caused by the stellar activity (see the examples in four bottom right panels of Fig. 13). The rest of the stars in their sample we would classify as ROTM, ROTS and ROT stars with only insignificant contamination of GDOR. In general, variability of a significant part of stars in the VAR class can be actually caused by the stellar activity but these variations have usually small amplitudes and the classification is not trustworthy. If we assume that all the stars from the sample of Bradley et al. (2015) classified by us as VAR are rotational variables, then the agreement with their study would be very good.

Wrong classification can be a serious issue in statistical studies and in training procedures based on the machine learning and neural networks methods. All the issues and discrepancies described above show that a commonly accepted methodology and classification system is desired. It is also the reason why our classification is rather conservative. Theoretical limits for the frequencies of GDOR pulsations, would be very helpful to distinguish between rotation and pulsations in a significant part of stars. It is worth to mention that we have not noticed any flare in the light curves of the sample stars.

8. Conclusions and future prospects

We performed a careful individual classification of 5923 A-F stars (temperatures between 6000 and 10000 K) brighter than 11 mag located close and in the northern TESS CVZ. The classification is based on the TESS photometric data and the properties of the frequency spectra. We largely discussed the data, crowding, the effects of residual variations caused by improper data reduction, aperture definition and the influence of these effects on the classification of the variable stars. We also largely discuss differences and similarities between the classes and pay a special attention to proper classification. We do not aim to study variability classes in detail and also do not highlight any particular star. We also do not show any of the interesting cases. These remain for dedicated studies.

We adopted the VSX classification scheme. We did not deal with the morphological classification of the variable stars within the variability classes as was done by the previous authors (e.g. Balona et al. 2011; Bradley et al. 2015). Our classification of the intrinsic variability is based on the assumption of the basic physical phenomena, i.e. rotation and pulsations. We introduced three classes of rotationally modulated stars: stars with stable chemical spots (ROTM), with regular brightness variations (ROT) and stars showing semi-regular variations assumed to be caused by forming/ceasing of the spots in combination with differential rotation (ROTS).

Our main results and findings can be summarized as follows:

- The PDCSAP data with different cadence are generally different not only in amplitude and cadence. Mainly 30-min data suffers from lots of residual variability that is not coming from the stars. This can lead to false positives and wrong classification.
- We provide clear and well defined classification scheme and methodology for a proper classification of the A-F variable stars based on the light curve shape and corresponding Fourier transform (Tables 2-4).

¹⁰ We checked only first 200 stars from the list of Balona (2013).

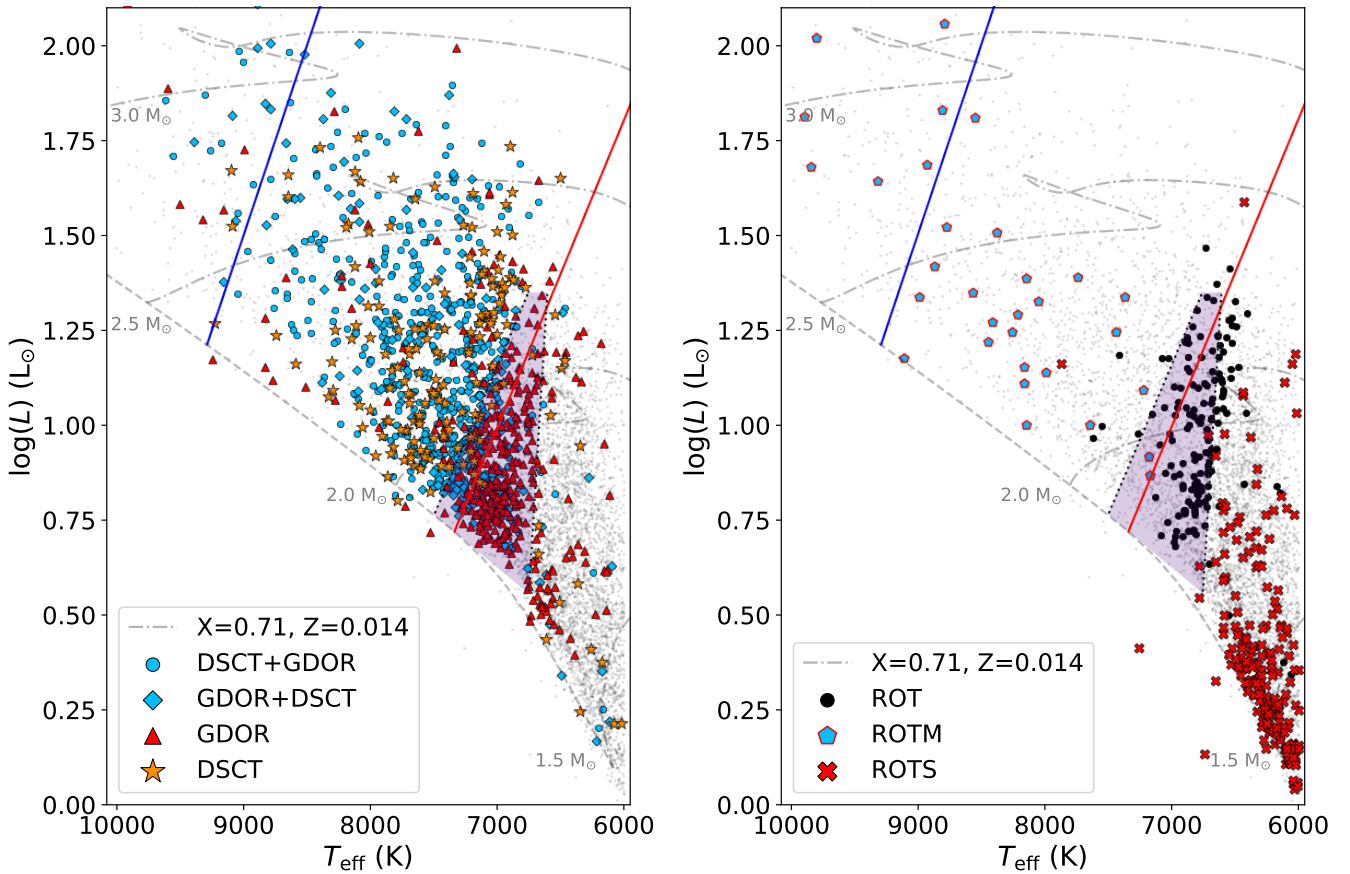


Fig. 11. Hertzsprung-Russel diagram showing pulsating stars (left panel) and rotationally modulated stars (right-hand panel). The dashed line shows the ZAMS, dashed lines show isochrones with different masses, all taken from Murphy et al. (2019). The blue and red continuous lines show the empirical boundaries of the instability strip determined by Murphy et al. (2019). The shaded area enclosed by the dotted lines shows the GDOR instability strip following Dupret et al. (2005). The grey dots show all stars including non-variable stars in our sample.

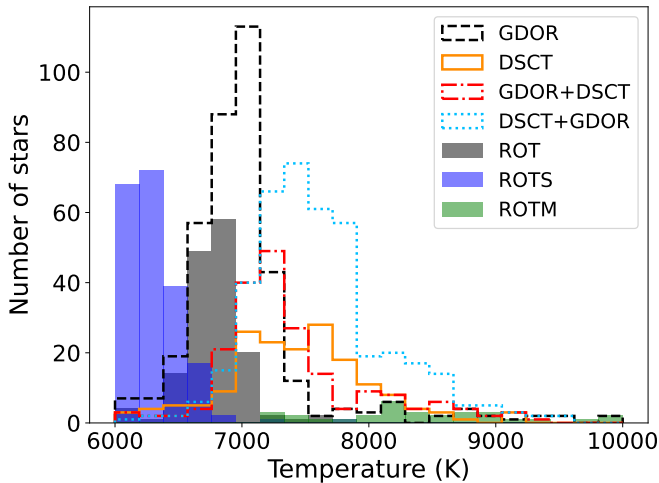


Fig. 12. Distribution of the stars with respect to their temperature.

- We found that the identification of the real pulsation frequencies above the Nyquist limit based purely on the amplitudes of the corresponding peaks in the FT can be wrong in up to 50 % cases.
- We identified a new (sub)class of variables showing regular periodic light curve shape and harmonics of the basic frequency in the FT. First we assumed that these variations must be connected with rotation but the position of these stars

close to and within the GDOR instability strip suggests that the variations are likely caused by pulsations. ROT stars have longer periods (1.7 vs 0.74 days), smaller amplitudes (1.5 vs 9.8 mmag) and are cooler in average (6777 vs 7043 K) than GDOR stars. The position of the stars in the HRD also suggests that the idea of co-rotating structures governed by high-order magnetic multipoles (Mikulášek et al. 2020; Krtićka et al. 2022) likely cannot explain the variations in these relatively cool stars that are not expected to have strong stellar winds.

- Measurements of $v \sin i$ of 4 stars showing semi-regular brightness variations and unresolved groups of peaks near the harmonics of the basic frequency give a hint that the observed light variations may be rather linked with rotation, than with pulsations. Stars in this group, called ROTS, can be mostly easily recognized from the GDOR stars.
- If the model of the light curve provides physically plausible results, there is no way how to unambiguously distinguish between ellipsoidal variables and ROTM types purely on the basis of single-channel photometry. We demonstrated this issue on IP Dra and generated models (Fig. 7).

On the comparison with previous studies, we demonstrated that a commonly accepted classification scheme should be agreed. Our approach offers a clear and well defined system of classification with many examples. There still might be spurious cases, mainly considering GDOR, ROTS and ROT classes, however, our sample should be clear of such ambiguous stars since

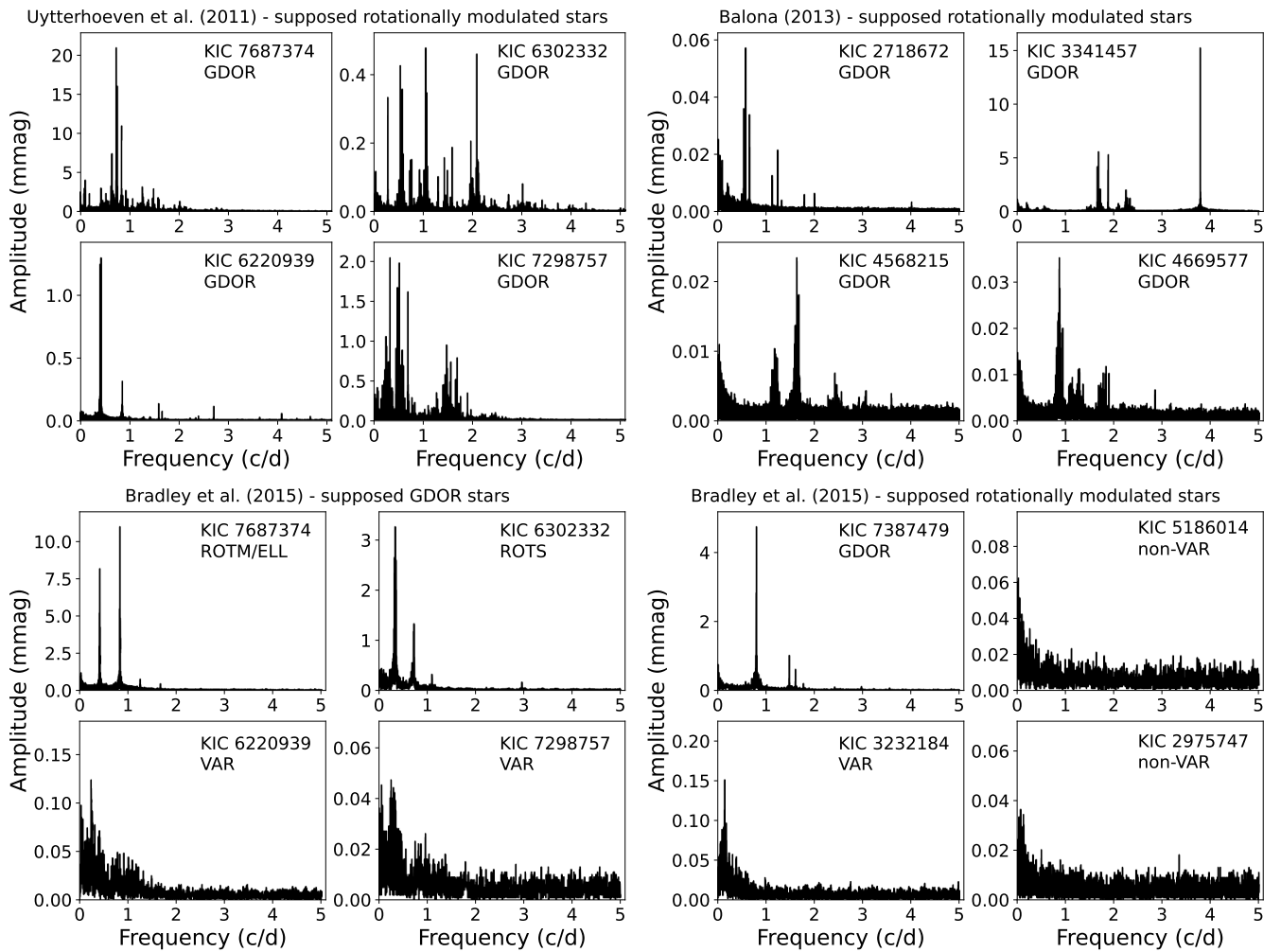


Fig. 13. Frequency spectra of stars observed by the *Kepler* mission and classified in previous studies (shown on the top of every four plots). The labels give how the stars would be classified using our methodology.

we classified the spurious cases as VAR. The theoretical study of the limits of g -mode pulsations and all the possible patterns that can be expected in the FT would be very helpful in future to better distinguish between rotation and pulsations. The only way how to reliably classify the variable stars is in detailed investigation case by case including spectroscopic data. We warn about blind usage of the (mainly long-cadence) TESS data.

The approach presented in the paper is rather conservative. Our groups of stars provide good and trustworthy samples of stars without significant contamination that is suitable for statistical studies and training of the neural networks. We are dealing with spectroscopic observations and detail investigation of particularly interesting stars identified during the analysis of the data. We will perform the same analysis for the southern TESS CVZ.

Acknowledgements. MS acknowledges the support by Inter-transfer grant no LTT-20015. MM acknowledges the support by MEYS (Czech Republic) under the project MEYS LTT17006. This paper includes data collected with the TESS mission. Funding for the TESS mission is provided by the NASA Explorer Program. Funding for the TESS Asteroseismic Science Operations Centre is provided by the Danish National Research Foundation (Grant agreement no.: DNRF106), ESA PRODEX (PEA 4000119301) and Stellar Astrophysics Centre (SAC) at Aarhus University. We thank the TESS team and staff and TASC/TASOC for their support of the present work. We also thank the TASC WG4 team for their contribution to the selection of targets for 2-min observations. The TESS data were obtained from the MAST data archive at the Space Telescope Science Institute (STScI). We acknowledge the usage of the data taken

with the Perek telescope at the Astronomical Institute of the Czech Academy of Sciences in Ondřejov and would like to thank the observers for their work.

References

- Antoci, V., Cunha, M., Houdek, G., et al. 2014, *ApJ*, 796, 118
- Audenaert, J., Kuzlewicz, J. S., Handberg, R., et al. 2021, *AJ*, 162, 209
- Balmforth, N. J., Cunha, M. S., Dolez, N., Gough, D. O., & Vauclair, S. 2001, *MNRAS*, 323, 362
- Balona, L. A. 2011, *MNRAS*, 415, 1691
- Balona, L. A. 2012, *MNRAS*, 423, 3420
- Balona, L. A. 2013, *MNRAS*, 431, 2240
- Balona, L. A. 2014, *MNRAS*, 437, 1476
- Balona, L. A. 2022, *MNRAS*, 510, 5743
- Balona, L. A., Guzik, J. A., Uytterhoeven, K., et al. 2011, *MNRAS*, 415, 3531
- Balona, L. A., Krisciunas, K., & Cousins, A. W. J. 1994, *MNRAS*, 270, 905
- Balona, L. A. & Nemeč, J. M. 2012, *MNRAS*, 426, 2413
- Barentsen, G. & Lightcurve Collaboration. 2020, in *American Astronomical Society Meeting Abstracts*, Vol. 235, American Astronomical Society Meeting Abstracts #235, 409.04
- Beech, M. 1985, *Ap&SS*, 117, 69
- Blanco-Cuaresma, S. 2019, *MNRAS*, 486, 2075
- Blanco-Cuaresma, S., Soubiran, C., Heiter, U., & Jofré, P. 2014, *A&A*, 569, A111
- Boch, T., Pineau, F., & Derriere, S. 2012, in *Astronomical Society of the Pacific Conference Series*, Vol. 461, *Astronomical Data Analysis Software and Systems XXI*, ed. P. Ballester, D. Egret, & N. P. F. Lorente, 291
- Borucki, W. J., Koch, D., Basri, G., et al. 2010, *Science*, 327, 977
- Bouabid, M. P., Dupret, M. A., Salmon, S., et al. 2013, *MNRAS*, 429, 2500

- Bowman, D. M. 2017, *Amplitude Modulation of Pulsation Modes in Delta Scuti Stars*
- Bradley, P. A., Guzik, J. A., Miles, L. F., et al. 2015, *AJ*, 149, 68
- Breger, M. 2000, in *Astronomical Society of the Pacific Conference Series*, Vol. 210, *Delta Scuti and Related Stars*, ed. M. Breger & M. Montgomery, 3
- Breger, M., Stich, J., Garrido, R., et al. 1993, *A&A*, 271, 482
- Cox, J. P. 1963, *ApJ*, 138, 487
- Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al. 2012, *Research in Astronomy and Astrophysics*, 12, 1197
- Dal, H. A. & Sipahi, E. 2013, *PASA*, 30, e016
- De Medeiros, J. R., Ferreira Lopes, C. E., Leão, I. C., et al. 2013, *A&A*, 555, A63
- Debusscher, J., Blomme, J., Aerts, C., & De Ridder, J. 2011, *A&A*, 529, A89
- Dupret, M. A., Grigahcène, A., Garrido, R., Gabriel, M., & Scuflaire, R. 2005, *A&A*, 435, 927
- Frolov, M. S. & Irkaev, B. N. 1984, *Information Bulletin on Variable Stars*, 2462, 1
- Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, *A&A*, 616, A1
- Gray, R. O. & Corbally, C. J. 1994, *AJ*, 107, 742
- Gray, R. O. & Corbally, C. J. 2014, *AJ*, 147, 80
- Grigahcène, A., Antoci, V., Balona, L., et al. 2010, *ApJ*, 713, L192
- Gustafsson, B., Edvardsson, B., Eriksson, K., et al. 2008, *A&A*, 486, 951
- Guzik, J. A., Kaye, A. B., Bradley, P. A., Cox, A. N., & Neuforge, C. 2000, *ApJ*, 542, L57
- Handler, G. 2009, *MNRAS*, 398, 1339
- Henry, G. W. & Fekel, F. C. 2005, *AJ*, 129, 2026
- Henry, G. W., Fekel, F. C., & Henry, S. M. 2011, *AJ*, 142, 39
- Houdek, G. 2000, in *Astronomical Society of the Pacific Conference Series*, Vol. 210, *Delta Scuti and Related Stars*, ed. M. Breger & M. Montgomery, 454
- Huang, C. X., Vanderburg, A., Pál, A., et al. 2020a, *Research Notes of the American Astronomical Society*, 4, 204
- Huang, C. X., Vanderburg, A., Pál, A., et al. 2020b, *Research Notes of the American Astronomical Society*, 4, 206
- Hümmerich, S., Mikulášek, Z., Paunzen, E., et al. 2018, *A&A*, 619, A98
- Jagelka, M., Mikulášek, Z., Hümmerich, S., & Paunzen, E. 2019, *A&A*, 622, A199
- Jenkins, J. M. & et al. 2020, *Kepler Science Document KSCI-19081-003*, *Kepler Science Document KSCI-19081-003*
- Jenkins, J. M., Twicken, J. D., McCauliff, S., et al. 2016, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 9913, *Software and Cyberinfrastructure for Astronomy IV*, ed. G. Chiozzi & J. C. Guzman, 99133E
- Kabáth, P., Skarka, M., Sabotta, S., et al. 2020, *PASP*, 132, 035002
- Kaye, A. B., Handler, G., Krisciunas, K., Poretti, E., & Zerbi, F. M. 1999, *PASP*, 111, 840
- Kinemuchi, K., Barclay, T., Fanelli, M., et al. 2012, *PASP*, 124, 963
- Kjurkchieva, D. & Marchev, D. 2014, *Information Bulletin on Variable Stars*, 6096, 1
- Kochukhov, O. 2011, in *Physics of Sun and Star Spots*, ed. D. Prasad Choudhary & K. G. Strassmeier, Vol. 273, 249–255
- Krtićka, J., Mikulášek, Z., Kurfürst, P., & Oksala, M. E. 2022, *A&A*, 659, A37
- Krtićka, J., Mikulášek, Z., Lüftinger, T., & Jagelka, M. 2015, *A&A*, 576, A82
- Krtićka, J., Mikulášek, Z., Zverko, J., & Žižňovský, J. 2007, *A&A*, 470, 1089
- Kurtz, D. W. 1982, *MNRAS*, 200, 807
- Li, X.-Z. & Liu, L. 2021, *New Astronomy*, 84, 101539
- Lightkurve Collaboration, Cardoso, J. V. d. M., Hedges, C., et al. 2018, *Lightkurve: Kepler and TESS time series analysis in Python*, *Astrophysics Source Code Library*
- Lomb, N. R. 1976, *Ap&SS*, 39, 447
- Mathys, G. 2017, *A&A*, 601, A14
- Mathys, G., Kurtz, D. W., & Holdsworth, D. L. 2020, *A&A*, 639, A31
- Michaud, G. 1970, *ApJ*, 160, 641
- Mikulášek, Z., Krtićka, J., Shultz, M. E., et al. 2020, in *Stellar Magnetism: A Workshop in Honour of the Career and Contributions of John D. Landstreet*, ed. G. Wade, E. Alecian, D. Bohlender, & A. Sigut, Vol. 11, 46–53
- Molnár, L., Bódi, A., Pál, A., et al. 2022, *ApJS*, 258, 8
- Morris, S. L. 1985, *ApJ*, 295, 143
- Murphy, S. J. 2015, *MNRAS*, 453, 2569
- Murphy, S. J., Hey, D., Van Reeth, T., & Bedding, T. R. 2019, *MNRAS*, 485, 2380
- Paunzen, E., Bernhard, K., Hümmerich, S., et al. 2020, *MNRAS*, 499, 3976
- Pedersen, M. G., Antoci, V., Korhonen, H., et al. 2017, *MNRAS*, 466, 3060
- Petersen, J. O. & Christensen-Dalsgaard, J. 1996, *A&A*, 312, 463
- Pineau, F.-X., Boch, T., Derrière, S., & Schaaff, A. 2020, in *Astronomical Society of the Pacific Conference Series*, Vol. 522, *Astronomical Data Analysis Software and Systems XXVII*, ed. P. Ballester, J. Ibsen, M. Solar, & K. Shortridge, 125
- Plachy, E., Molnár, L., Bódi, A., et al. 2019, *ApJS*, 244, 32
- Preston, G. W. 1974, *ARA&A*, 12, 257
- Prvák, M., Liška, J., Krtićka, J., Mikulášek, Z., & Lüftinger, T. 2015, *A&A*, 584, A17
- Renson, P. & Manfroid, J. 2009a, *A&A*, 498, 961
- Renson, P. & Manfroid, J. 2009b, *A&A*, 498, 961
- Ricker, G. R., Winn, J. N., Vanderspek, R., et al. 2015, *Journal of Astronomical Telescopes, Instruments, and Systems*, 1, 014003
- Royer, F., Zorec, J., & Gómez, A. E. 2007, *A&A*, 463, 671
- Samus, N. N., Kazarovets, E. V., Durlevich, O. V., Kireeva, N. N., & Pastukhova, E. N. 2009, *VizieR Online Data Catalog*, B/gcvs
- Sánchez Arias, J. P., Córscico, A. H., & Althaus, L. G. 2017, *A&A*, 597, A29
- Scargle, J. D. 1982, *ApJ*, 263, 835
- Sikora, J., David-Uraz, A., Chowdhury, S., et al. 2019, *MNRAS*, 487, 4695
- Sikora, J., Wade, G. A., & Rowe, J. 2020, *MNRAS*, 498, 2456
- Smith, J. C., Stumpe, M. C., Van Cleve, J. E., et al. 2012, *PASP*, 124, 1000
- Stassun, K. G., Oelkers, R. J., Paegert, M., et al. 2019, *AJ*, 158, 138
- Stibbs, D. W. N. 1950, *MNRAS*, 110, 395
- Stumpe, M. C., Smith, J. C., Catanzarite, J. H., et al. 2014, *PASP*, 126, 100
- Trust, O., Jurua, E., De Cat, P., & Joshi, S. 2020, *MNRAS*, 492, 3143
- Twicken, J. D., Chandrasekaran, H., Jenkins, J. M., et al. 2010, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 7740, *Software and Cyberinfrastructure for Astronomy*, ed. N. M. Radziwill & A. Bridger, 77401U
- Uytterhoeven, K., Mathias, P., Baglin, A., et al. 2011a, *arXiv e-prints*, arXiv:1111.1840
- Uytterhoeven, K., Moya, A., Grigahcène, A., et al. 2011b, *A&A*, 534, A125
- Čokina, M., Fedurco, M., & Parimucha, Š. 2021, *A&A*, 652, A156
- Watson, C. L., Henden, A. A., & Price, A. 2006, *25th Annual Symposium, The Society for Astronomical Sciences*, 47
- Wenger, M., Ochsenbein, F., Egret, D., et al. 2000, *A&AS*, 143, 9
- Zhao, G., Zhao, Y.-H., Chu, Y.-Q., Jing, Y.-P., & Deng, L.-C. 2012, *Research in Astronomy and Astrophysics*, 12, 723

**Appendix A: Examples of typical light curves and
frequency spectra.**

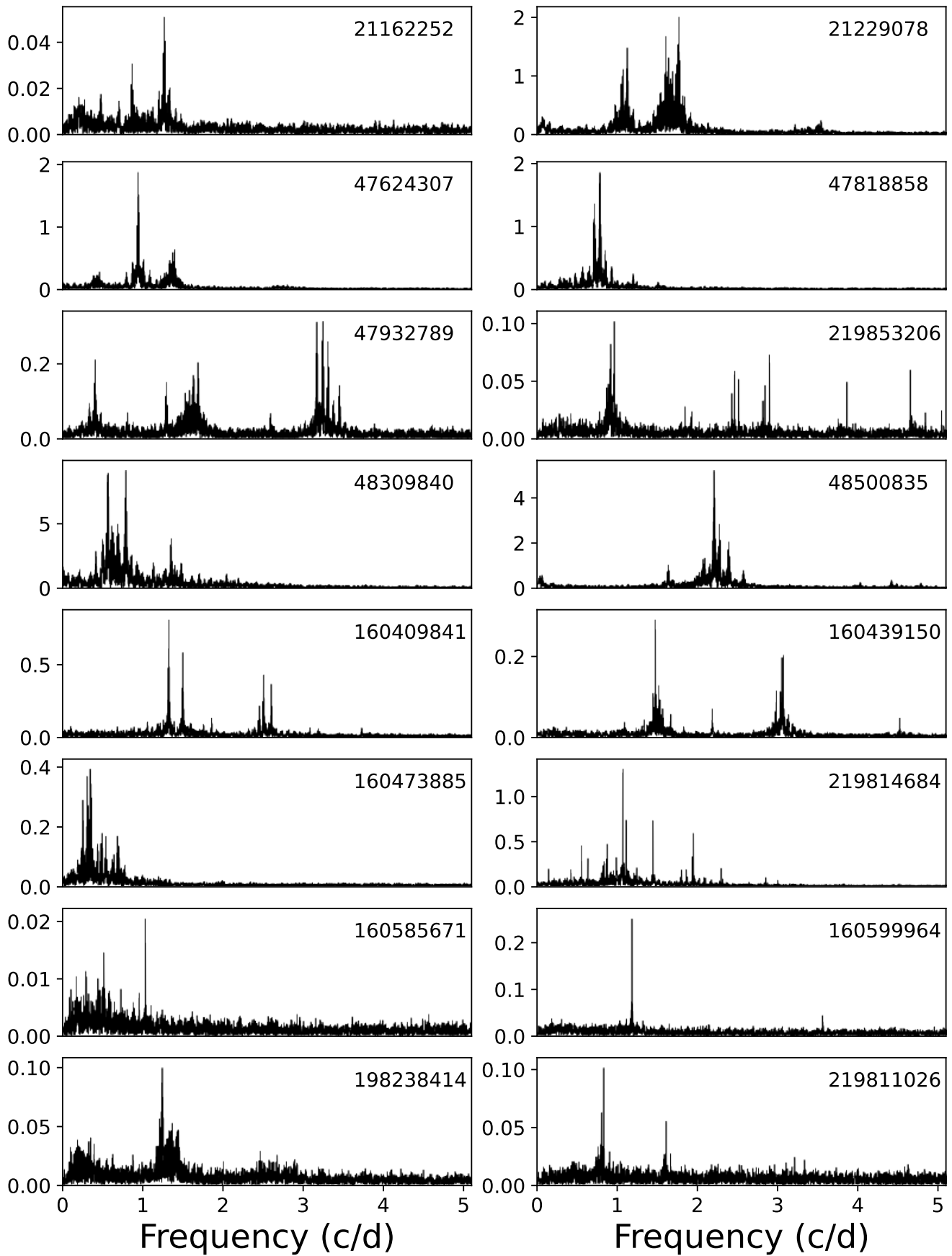


Fig. A.1. The typical frequency spectra of GDOR stars. The four most-bottom plots show less certain cases. The scale on the vertical axis is in mmag. The labels show the TIC numbers.

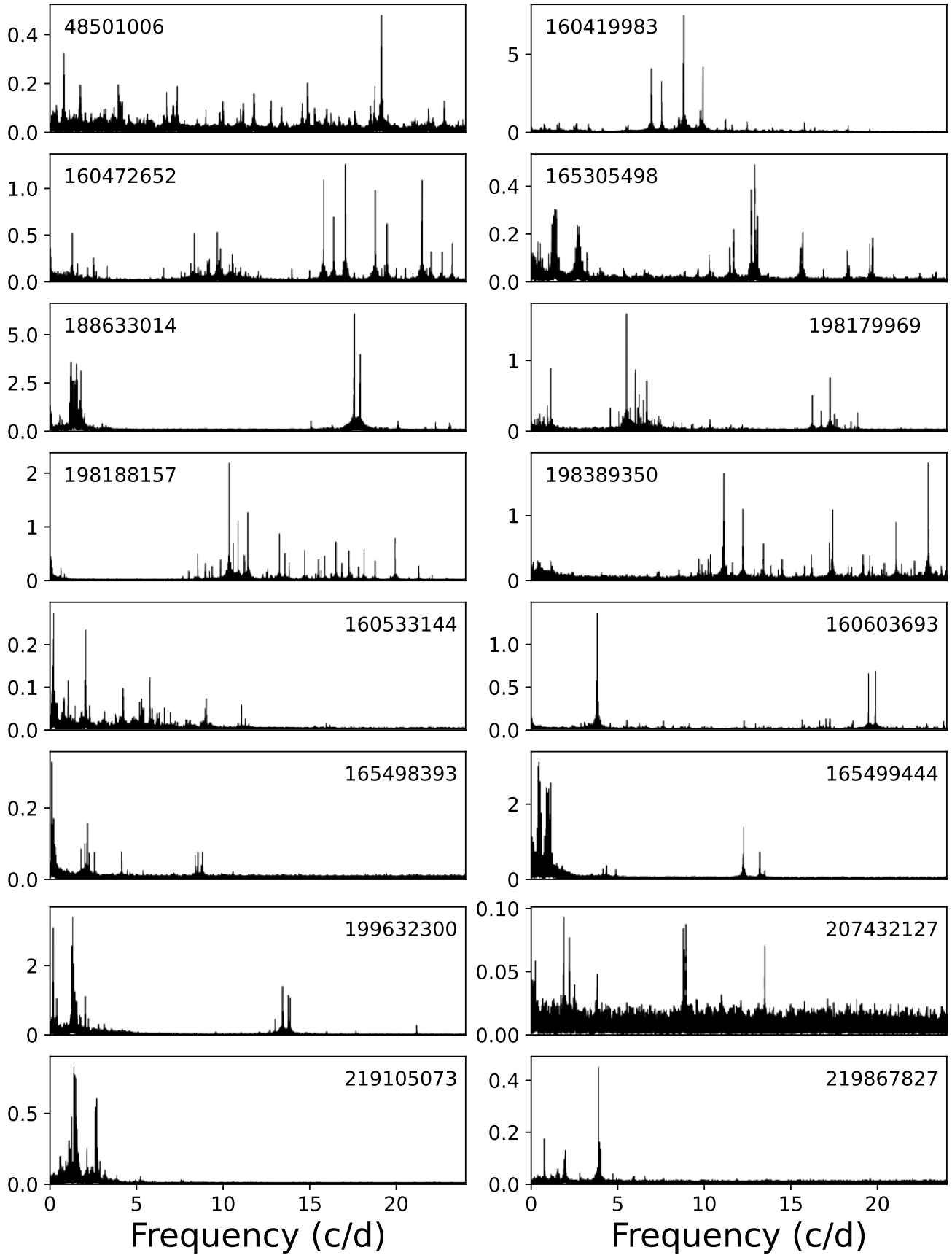


Fig. A.2. The typical frequency spectra of GDOR and DSCT Hybrid stars. The eight upper panels show DSCT dominant, while the eight bottom panels show the GDOR dominant hybrids. TIC 198188157 and 198389350 show weak peaks in the GDOR regime and, thus, are less certain hybrids. TIC 219105073 and 219867827 show only low-amplitude peaks in the DSCT regime and, thus, are less certain hybrids. The less certain hybrids can possibly be classified as pure GDOR or DSCT stars. The scale on the vertical axis is in mmag.

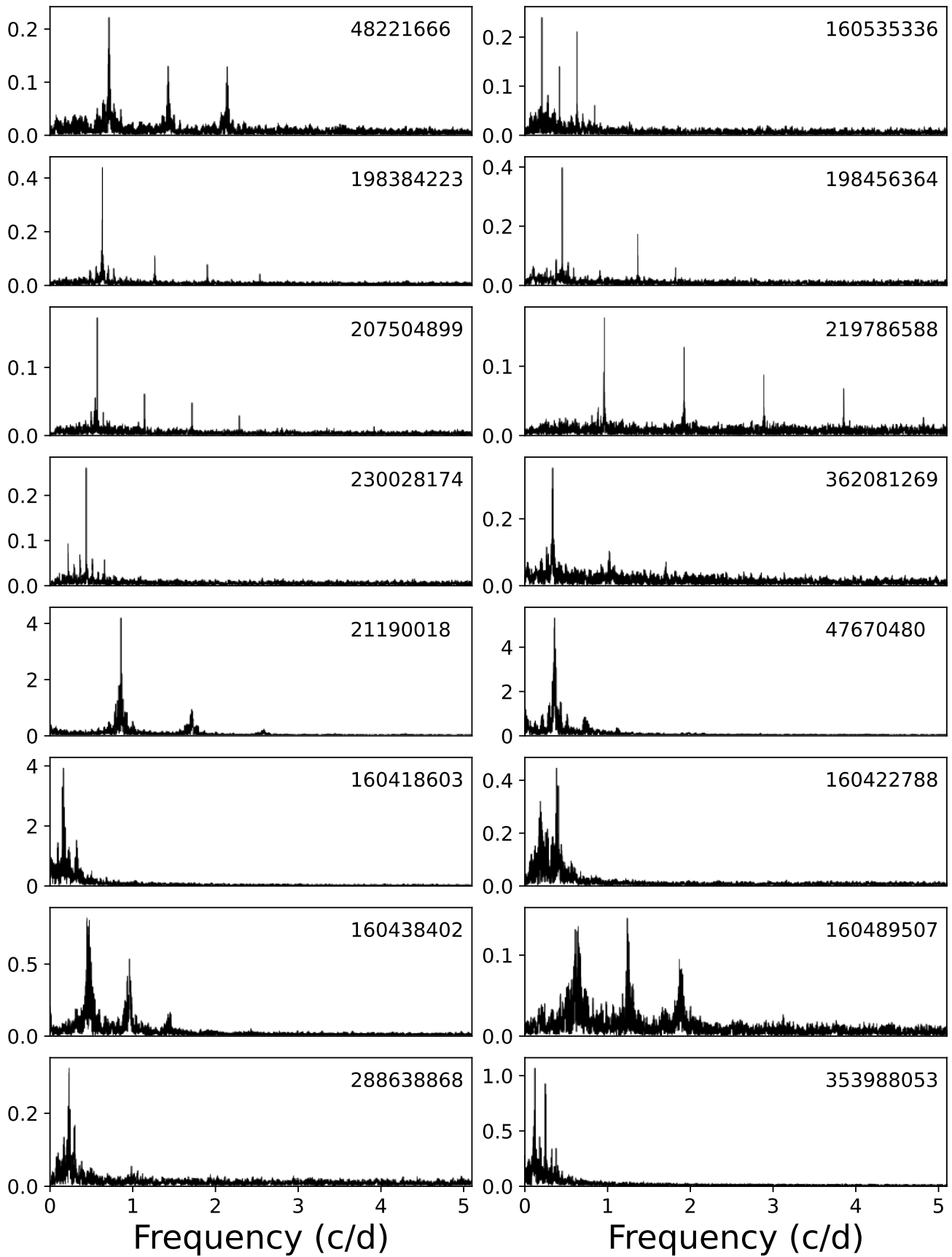


Fig. A.3. The typical frequency spectra of ROT (eight upper panels) and ROTS stars (eight bottom panels). The scale on the vertical axis is in mmag.

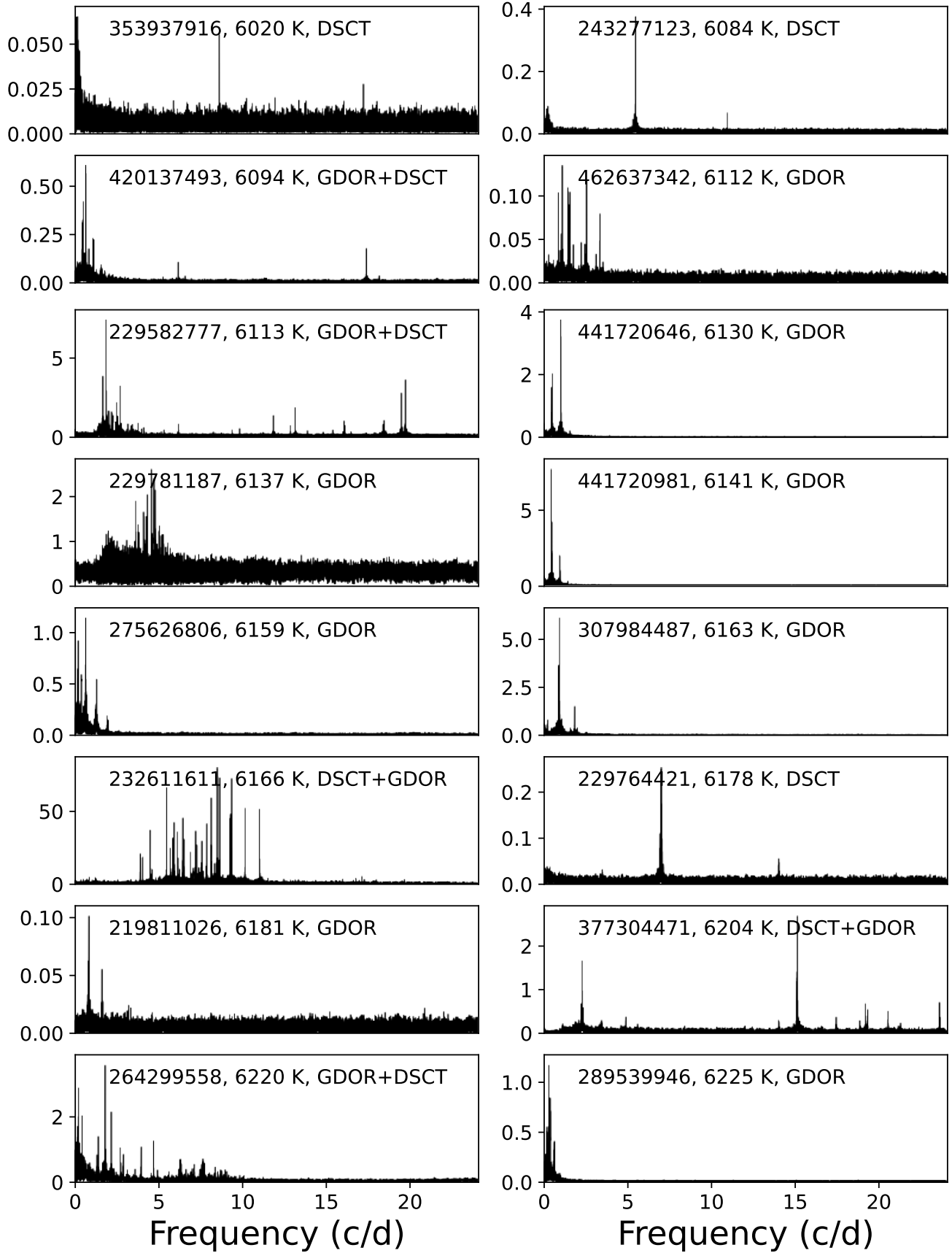


Fig. A.4. The frequency spectra of the coolest pulsating stars in our sample. The first number is the TIC number, the second number gives the temperature from TIC catalogue. The scale on the vertical axis is in mmag.