Mon. Not. R. Astron. Soc. **000**, 1–8 (2011) Printed 17 March 2011 (MN LaTeX style file v2.2)

The *Kepler* view of γ Doradus stars

L. A. Balona[1], J. A. Guzik[2], K. Uytterhoeven[3,4],
J. C. Smith[5], P. Tenenbaum[5], J. D. Twicken[5]
[1]*South African Astronomical Observatory, P.O. Box 9, Observatory 7935, Cape Town, South Africa*
[2]*Los Alamos National Laboratory, X-2 MS T-086, Los Alamos, NM 87545-2345, USA*
[3]*Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot; IRFU/SAp, Centre de Saclay, 91191, Gif-sur-Yvette, France*
[4]*Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, 79104 Freiburg, Germany*
[5]*SETI Institute/NASA Ames Research Center, Moffett Field, CA 94035*

ABSTRACT
Visual classification of over 10 000 stars in the *Kepler* database has revealed a class of stars with almost mono-periodic light variations and characteristic beating. A subset of these stars have a larger light amplitude and asymmetric light curves with larger variation in maximum brightness than in minimum brightness. The beating is mostly a result of two dominant, closely-spaced frequencies. A third group of stars shows multiple low frequencies of comparable amplitudes. All three types of star fall in the region of the HR diagram where γ Dor stars are found and we therefore identify them as γ Dor variables. However, stars with migrating starspots also have symmetric light curves with beats, so it is likely that the sample is contaminated by non-pulsating stars of this type. If we assume that the dominant frequency in stars with beats is the rotational frequency, the resulting distribution of equatorial rotational velocities matches that of field stars of similar temperature and luminosity. We therefore conclude that the pulsation periods of these stars must be close to their rotational periods. The third group with multiple frequencies may be slowly-rotating γ Dor stars. This investigation is closely related to the presence of low-frequencies in δ Scuti stars which we briefly discuss.

Key words: Kepler – stars: oscillations – stars: variables: γ Doradus

1 INTRODUCTION

The *Kepler* mission is designed to detect Earth-like planets around solar-type stars by the transit method (Koch et al. 2010). Time series photometry of long duration which is continuous, homogeneous and evenly spaced and of unprecedented accuracy has been obtained for a very large number of stars in the *Kepler* field of view. Such data presents an ideal opportunity to study the variability of main sequence A–F stars. Most of the photometry has been obtained with exposures of about 30 min duration (long-cadence mode), with a much smaller sample of stars observed with approximately 1 min exposure times (short-cadence mode). The *Kepler Input Catalogue* (KIC) contains derived values of effective temperature, $T_{\rm eff}$, gravity, $\log g$ and radius for most stars. These parameters were determined by modeling Sloan-like multicolour photometry. The effective temperatures are reliable for $T_{\rm eff} < 8000$ K but deteriorate for hotter stars, becoming unreliable for $T_{\rm eff} > 10\,000$ K (Balona et al. 2011).

The γ Doradus stars are a group of pulsating F-type stars. They lie in a fairly small region on, or just above, the main sequence that partly overlaps the cool edge of the δ Scuti instability strip. They pulsate in multiple nonradial g modes with periods in the range 0.3–3.0 d. In this region of the HR diagram, the thin convective zones associated with partial ionization of HeI and H begin to merge and form a single larger convective envelope. The driving mechanism in γ Dor stars is caused by a modulation of radiative flux from the interior of the star due to the convection zone, a mechanism known as convective blocking (Guzik et al. 2000).

A first calculation of the location of instability strip for γ Dor stars was obtained by Warner et al. (2003) using frozen-in convection. Agreement between the observed and theoretical instability strip is poor: only about half the γ Dor stars fall within the instability region. The frozen-in approximation for convection is not valid in much of the envelope because the lifetime of the convective elements becomes shorter than the pulsation period. Using a time-dependent convection (TDC) theory applied to a model of a 1.6 $M_\odot$ star, unstable g modes for $l = 1$ and $l = 2$ are obtained with frequencies in the range 0.5–2 d^{-1}, which is typical of γ Dor stars (Dupret et al. 2005). In the models, frequencies of $l = 2$ modes are higher than those of $l = 1$ modes. The time-dependent theory essentially confirms convective flux blocking as the driving mechanism in γ Dor stars.

It is the location of the base of the convective envelope which seems to be the key element in driving γ Dor pulsations. In the middle of the instability strip, the base is located in the transition region where the thermal relaxation time roughly matches the pulsation periods. Driving is therefore very efficient. For hotter stars, the convective envelope is thinner which means that the thermal relaxation time is shorter than the pulsation period. The heat capacity is small and driving is inefficient. Since the size of the convection zone is determined by the adopted mixing length, the resulting blue edge is sensitive to the adopted mixing length, α (Dupret et al. 2004). The stability of models at the red edge has a different origin. For the cooler models, radiative damping of g modes overcomes driving by convective blocking and stabilizes the model. Good agreement with ground-based observations is found for $\alpha = 2$. For $\alpha = 1.5$ and lower, the calculated instability strips do not match the observations at all (Dupret et al. 2004).

In addition to low frequencies typical of γ Dor variables, high-frequency δ Sct pulsations have been found in ground-based observations of a few stars. These γ Dor/δ Sct hybrids are of particular interest as they can potentially probe a large region of the stellar interior. Pulsations in both low-frequency g modes and high-frequency p modes were found in models of a 1.6 $M_\odot$ star using TDC (Dupret et al. 2005). Hybrid behaviour was also found in a 1.54 $M_\odot$ model (Bouabid et al. 2009). In these models there is a gap from about 5 d^{-1} to 10 d^{-1} where no unstable mode is found. There is some driving of the low-frequency g modes due to the κ mechanism operating on the Fe opacity bump, but this is not sufficient to destabilize the modes. Most of the driving occurs at the base of the convective envelope due to the convective blocking mechanism. Driving of the p modes occurs both by the convective blocking mechanism and the κ mechanism operating in the He partial ionization zone. The stability of modes between the two regions is due to efficient damping in the inner region of the star.

A preliminary analysis of δ Sct stars observed by *Kepler* (Grigahcène et al. 2010) shows that in most of these stars low-frequency multiperiodic variations are present, usually of low-amplitude. The nature of these variations suggest pulsation. If the variations are due to pulsation, then hybrid behaviour is the rule rather than the exception, but no pulsation mechanism is known which can drive low-frequency oscillations for stars hotter than about 7 400 K, the hot edge of the γ Doradus instability strip. Yet these low-frequency variations are present in δ Scuti stars with the highest effective temperatures.

In order to shed light on this problem, it is important to investigate a sample of pure γ Dor stars in the *Kepler* database. Unless we can recognize and understand the light curves of pure γ Dor stars, we are unlikely to recognize the difference between a genuine δ Sct/γ Dor hybrid and a δ Sct star in which the low-frequencies are not due to pulsation. As a first step in identifying γ Dor stars in the *Kepler* data base, we have compiled a catalogue of over 10 000 stars. For each star in the catalogue, we assign a classification based mostly on the visual appearance of the light curve. We emphasise that this classification was done purely by visual inspection of the light curves and periodograms. Recently, Debosscher et al. (2011) has classified a large number of *Kepler* stars automatically. We were completely unaware of this work: our classification is completely independent and uses quite different, human, criteria.

During the course of this work we noticed a group of stars with very distinctive light curves. These light curves are characterized by frequencies typical of those found in γ Dor stars but with beating. In many stars the light curve is asymmetric with large variations in maximum brightness and much smaller variations in minimum brightness. We call this group the ASYM group. When we plotted ASYM stars in the HR diagram, we found them to be located in the same region as ground-based γ Dor stars. Most of the stars with beats have more more symmetric light curves; we call these the SYM group. These stars, too, mostly fall in the known γ Dor instability strip, but are not as confined as the ASYM stars.

Stars with light curves just described are, of course, not uncommon in the literature. Examples can be found in Blomme et al. (2010), Debosscher et al. (2009) and Degroote et al. (2009). In some cases these can be identified with stars in the γ Dor instability strip, but more often they belong to stars in the Be and SPB class. A close examination of ground-based light curves and periodograms of γ Dor stars does show, in retrospect, that many of these stars have light curves of the SYM and ASYM types, but are very difficult to recognize because of the frequent data gaps. It is not so much the distinctive shape of the light curve that is important, but the fact that the vast majority of them lie in the region of the HR diagram occupied by ground-based observations of γ Dor stars.

The periodograms of these two groups of stars are dominated by just one or two closely-spaced frequencies, whereas we were expecting γ Dor stars to show many low-frequencies with comparable amplitudes. Indeed, we did find just such a group of stars, which we call the MULT group, but with relatively few members. This group of stars fall into two distinct regions in the HR diagram: the γ Dor instability strip and in the red giant region. We presume the latter stars are giant solar-like pulsators.

In this paper we discuss the three groups of stars mentioned above. We investigate their locations in the HR diagram and the relationship between the dominant frequency in the light curve and the rotational frequency.

2 THE DATA

The *Kepler* satellite is in a 370 d orbit around the Sun. In order to maintain the same field of view and yet keep its solar panels towards the Sun, a spacecraft "roll" is performed at certain intervals. The period between rolls is called a "quarter" which is sometimes split into approximately one-month "thirds". Most of the data we will be discussing were obtained during the initial 9-day commissioning period, Q0, and the first 30-d survey period, Q1. The data are available in "uncalibrated" and "calibrated" form. The calibrated data suffers from artifacts caused by the processing and is not used here. An overview of the *Kepler* science processing pipeline is given in Jenkins et al. (2010).

There are 2075 stars with $5\,000 < T_{\rm eff} < 10\,000$ K in the KIC which were observed in short-cadence (SC) mode. Over 30 000 stars in this temperature range have been observed in long-cadence (LC) mode. In order to select a reasonably-sized sample for visual classification, we decided to use all the SC stars in this temperature range and all the LC stars with $6\,500 < T_{\rm eff} < 10\,000$ K. The sample was extended to $T_{\rm eff} = 5\,000$ K by selecting stars with $Kp < 12$ mag. Some statistics of the sample are given in Table 1.

The *Kepler* data contains drifts and jumps which, to a large extent, can be corrected automatically. There is a zero-point difference between data in different quarters and the instrumental drift varies from quarter to quarter. The first step in correcting the data is to remove any linear trend within each quarter. Then we match the end of one quarter and the start of the following quarter. Any linear trend in the combined data is removed. The overall shape of the light curve is derived by fitting a spline curve to medians of the data in 0.25-d intervals. Using this curve, outliers are removed by an iterative procedure. The corrected light curves were examined visually. For the most part, this rather simple procedure proved quite satisfactory. The light curves of stars which were not success-

Table 1. Numbers of stars in different temperature and cadence ranges.

$T_{\rm eff}$ range	Sp. Type	LC+SC	LC	SC
All		10976	8978	2075
$5000 < T_{\rm eff} < 6000$	G9–F9	2354	2286	87
$6000 < T_{\rm eff} < 6500$	F9–F5	3845	2912	961
$6500 < T_{\rm eff} < 7000$	F5–F1	3838	3417	430
$7000 < T_{\rm eff} < 7500$	F1–A8	1409	1143	281
$7500 < T_{\rm eff} < 8500$	A8–A3	1323	970	369
$8500 < T_{\rm eff} < 10000$	A3–A0	561	536	34

fully corrected in this way (e.g. eclipsing variables) were corrected manually. The procedure tends to dampen or remove very low frequencies, but frequencies above about 0.1 d^{-1} are not affected.

For the purposes of classification of the low-frequency variations we relied purely on visual inspection of the raw light curves, i.e., the *Kepler* uncalibrated data without the processing described in the previous paragraph. For stars which pulsate at high frequencies, e.g., δ Scuti and stars with solar-like oscillations, our classification is based on inspection of the periodogram of the data processed in the way just described. The vast majority of stars are clearly variable in the low-frequency regime (i.e. less than 5 d^{-1}). The variability is easily distinguished from instrumental drift which occurs over a longer timescale.

The length of the *Kepler* time series (which is about one month for most stars) places a lower limit of something like 0.1–0.2 d^{-1} on the frequencies. In other words, for frequencies lower than this range we cannot be sure whether the variation is intrinsic to the star or if it is an instrumental or processing artifact. For stars observed in LC mode, there is an upper limit of about 24 d^{-1} in frequency. For stars observed in SC mode this limit is about 700 d^{-1}.

3 LIGHT CURVES OF *KEPLER* STARS

Inspection of *Kepler* light curves of A–F stars, whether they be δ Sct stars or not, show that most of these stars are variable at low frequencies. In other words, the low frequencies seen in *Kepler* δ Sct stars does not depend on the presence of δ Sct pulsations and therefore unlikely to be due to combination frequencies. The fact that low frequencies are seen from the coolest G star to the hottest A star, indicates a very large instability strip if they are all attributed to pulsation. Of course, there could be different causes for these variations. Spotted stars and stars with active atmospheres are common among the G stars and cool F stars, so this might explain the low-frequency variations in these stars.

The A-type stars are not expected to have spots or be active because of their radiative atmospheres. Furthermore, the convective blocking mechanism ceases to operate in stars with effective temperatures higher than about 7 400 K, corresponding to spectral type around F0. For these reasons, the presence of low-frequency variations in A-type stars is a problem. An analysis of *Kepler* data of A-type stars indicates a close correlation between the dominant low frequency and the rotational frequency, suggesting that the low-frequency variations in A-type stars might be of rotational origin (Balona 2011). However, it turns out that the low frequencies in A-type δ Sct stars cannot be explained in this way. For some reason, it appears that the dominant low frequency in δ Sct stars is twice the rotational frequency. In fact, a significant fraction of A-type δ Sct stars show a low-amplitude peak at exactly half the dominant low

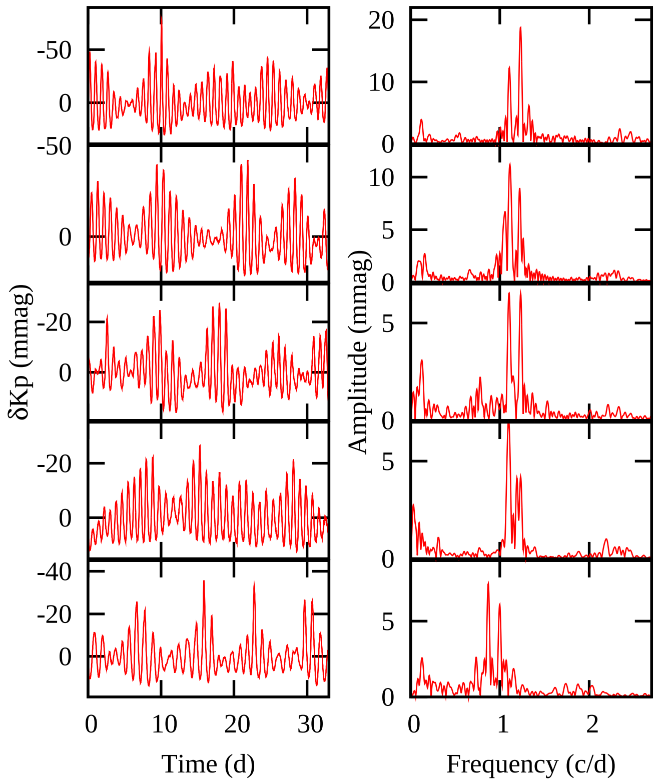

Figure 1. Left panel: γ Dor stars with asymmetric light curves (the ASYM group). Right panel: periodograms of these stars. Top to bottom: KIC 3441414, 4547348, 4661223, 5000456 and 5021374.

frequency which corresponds to the rotational frequency. Why such a quadrupole light distribution should be present in A-type δ Sct stars is not known (Balona 2011).

We have mentioned that there are quite a large number of stars in the *Kepler* data with very distinctive light curves - the ASYM group. Examples of light curves and periodograms of these stars are shown in Fig. 1. Note that the periodograms show just one or two dominant peaks. We found 137 stars of this type, nearly all of them in the range $6000 < T_{\rm eff} < 7500$ (1.5 percent of stars in this temperature range).

Among the F- and G-type stars in the *Kepler* data base there are many instances of light curves which can be represented by a superposition of two sinusoids with slightly different periods which also give rise to beating. In the literature, light curves of this type have been associated with migrating starspots (Strassmeier 2010). These light curves resemble the ASYM ones shown in Fig. 1 except that they are symmetric. More often than not, however, it is not possible to distinguish the traveling feature which characterizes variations due to migrating starspots. Instead, the light curve is quasi-periodic with beating and approximately symmetric with respect to the maxima and minima. Examples of light curves and periodograms for this SYM group of stars are shown in Fig. 2. Note that just as for the ASYM group, the periodogram is dominated by just one or two low frequencies. We found 1035 stars of the SYM type, most of them in the range $6000 < T_{\rm eff} < 7500$ (11.4 percent of stars in this temperature range).

There is no strict dividing line between the SYM and ASYM groups and the classification in terms of one or the other is rather subjective in borderline cases. It stands to reason that whatever

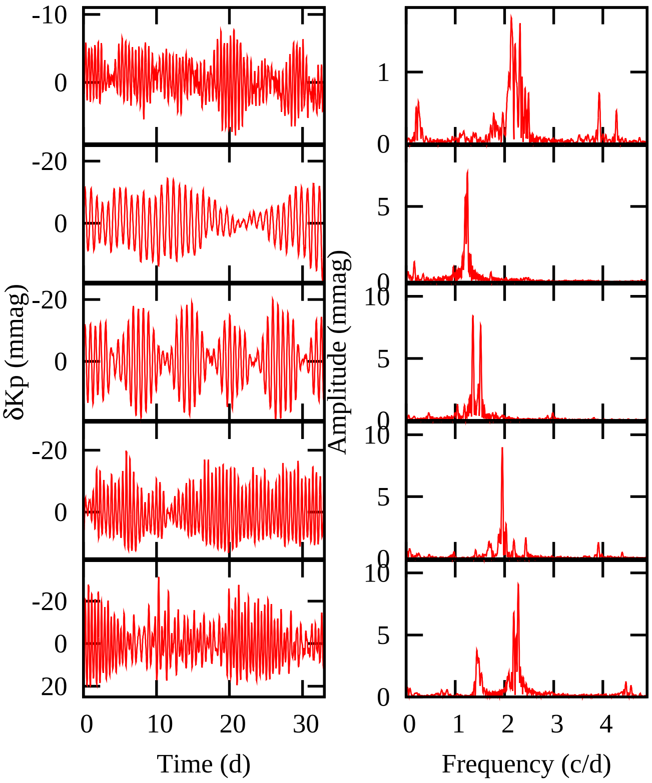

Figure 2. Left panel: stars with symmetric light curves (the SYM group). Right panel: periodograms of these stars. Top to bottom: KIC 4050047, 4930889, 6352430, 6380579 and 9962653.

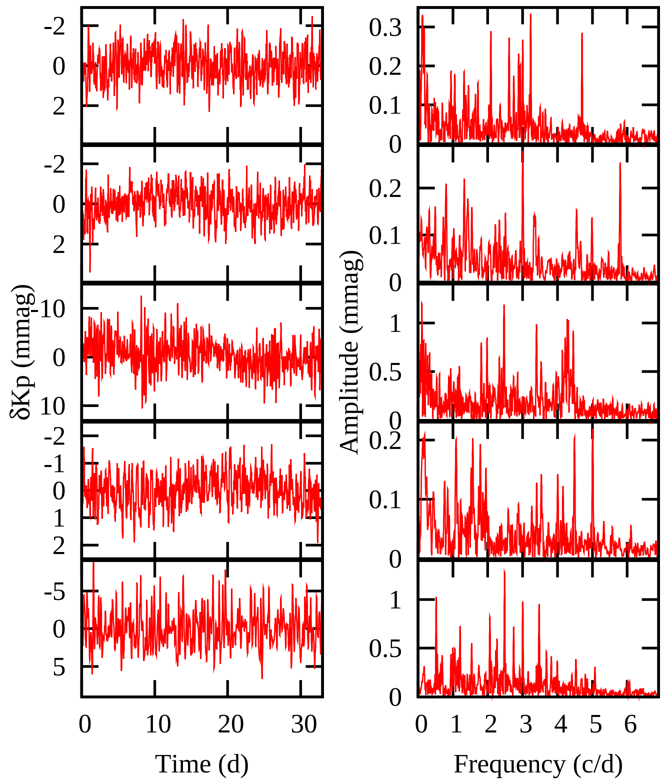

Figure 3. Light curves and periodograms of stars with multiple modes (the MULT group. Top to bottom: KIC 2282763, 3340360, 7975162, 8430119 and KIC 9092529.

mechanism gives rise to asymmetric light curves also gives rise to symmetric light curves. The ASYM light curves are not easily explained in terms of starspots and highly-asymmetric light curves have never been reported for these type of stars. Such asymmetry is found, for example, among the RRab stars and high-amplitude δ Scuti stars (HADS) and can be understood as a saturation effect in pulsational driving. When these stars are plotted in the HR diagram, they are located where one expects to find γ Dor stars (Fig. 4, top panel). We are thus confident in assuming that the variation in the ASYM group is due to pulsation and that they are, in fact, γ Dor stars.

Finally, our survey also uncovered a group of stars with multiple low frequencies with roughly equal amplitudes (the MULT group). These stars mostly lie in the region of the HR diagram in which γ Dor stars are located, though a sizable fraction appear to be red giants. Solar-like oscillations in red giants are expected to fall in the low frequency range. It is not possible to tell the difference in the light curves or periodograms between solar-like oscillations in red giants and multiperiodic γ Dor pulsations. Hence in our survey, based purely on the appearance of the light curves and periodogram, bot these types of star are classified as MULT. However, the KIC effective temperature offers a simple method of discriminating between the two types. Examples of light curves and periodograms of some stars in the MULT group within the γ Dor instability strip are shown in Fig. 3. We found 108 stars of this type in the γ Dor instability strip (1.2 percent of F-type stars), while 69 have $T_{\rm eff} < 6000$ K and are probably red giants with solar-like pulsations.

The location of these three groups of stars as well as the theoretical red and blue edges of the γ Dor instability strip (Dupret et al. 2004) is shown in Fig. 4. The theoretical edges do not quite match the observed distribution of stars, but this is not surprising. There are errors in $\log T_{\rm eff}$ and in $\log {\rm L/L_\odot}$ which causes a spread in the location of stars in this diagram. Moreover, the location of the theoretical red edge of the instability strip depends on the assumed mixing length which was chosen to match ground-based observations of the red edge. This choice needs to be revised in the light of the Fig. 4.

Also shown in Fig. 4 are all the stars in our catalogue which we have identified as δ Sct variables because of the presence of high frequencies ($\nu > 5$ d^{-1}). Many of these stars could be of the SX Phe type. It is not possible to discriminate between these stars and the classical δ Sct stars solely on the light curve. A large fraction of δ Sct stars lies blueward of the fundamental radial mode blue edge. These stars must be pulsating in higher-order radial and nonradial modes.

The distribution of the three types of star as a function of effective temperature is shown in Fig. 5. We note that the ASYM and MULT groups are relatively well confined with $6000 < T_{\rm eff} < 7500$ K. The MULT types with $T_{\rm eff} < 6000$ K form a separate distribution and represents solar-type oscillations in late G giants. The fact that ASYM and the hotter MULT stars are well confined in effective temperature is consistent with what one might have expected for stars in a well-defined instability strip. On the other hand, the SYM stars have a long tail extending towards high effective temperatures. We have already mentioned that rotating spotted stars have light curves which are indistinguishable from the SYM type and that stars with this type of light curve almost certainly

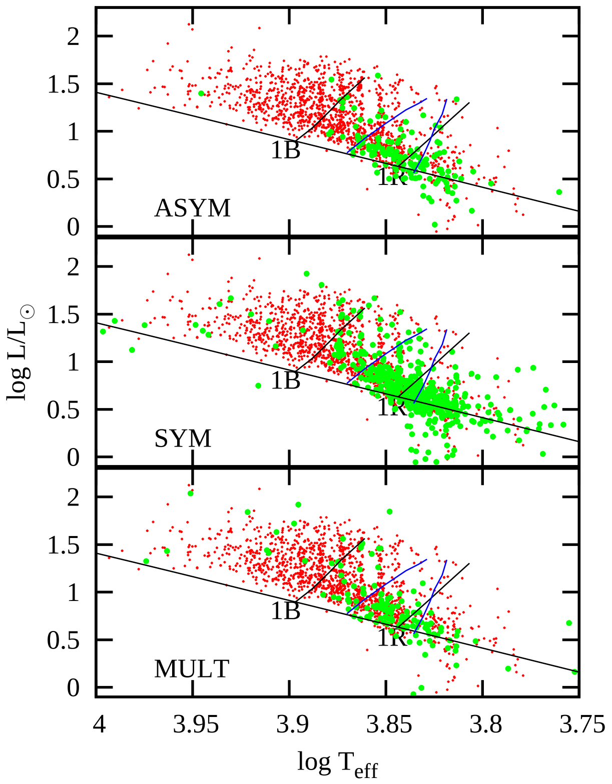

Figure 4. Location of γ Dor stars in the theoretical HR diagram. The small symbols are δ Scuti stars in the *Kepler* field of view. The lines marked 1B and 1R are the blue and red edges for fundamental radial mode pulsation and the curved lines are the blue and red edges of the γ Dor instability strip (Dupret et al. 2004). The straight line is the zero-age main sequence. The top panel shows the location of stars with asymmetric light curves. The middle panel shows the location of stars with symmetric light curves and the bottom panel those with multiple frequencies.

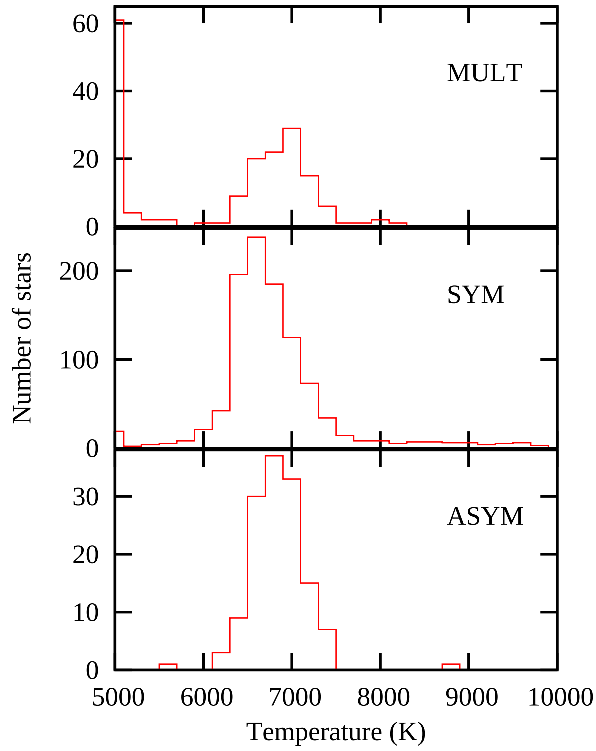

Figure 5. Distribution of the three groups of stars as a function of effective temperature.

comprise a mixture of γ Dor stars and spotted stars. The long tail at high effective temperatures is probably due to spotted stars alone. Balona (2011) shows that the photometric periods of these stars are consistent with their expected rotational periods.

4 FREQUENCY AND AMPLITUDE DISTRIBUTION

If the ASYM light curves are due to a saturation effect in pulsational driving, then the asymmetry should arise only for high amplitudes. The reason why HADS, for example, have such non-linear asymmetric light curves is because they are the δ Sct stars of highest amplitude. In the same way, if pulsation is the cause of the variation in ASYM stars, these stars should have larger amplitudes than the SYM type. The top panel of Fig. 6 shows the distribution of amplitudes of the main periodic component for ASYM and SYM stars. It can be seen that, indeed, the ASYM stars have much larger amplitudes than the SYM stars. This is not proof that the ASYM stars are pulsating, but it at least supports the notion that the asymmetry in the light curve might be due to non-linear saturation effects in pulsational driving.

The frequency distributions of the ASYM and SYM stars are also different (bottom panel of Fig. 6). The SYM type has a significantly wider range of frequencies. However, both classes have a maximum at about 1 d^{-1}. We may speculate that the wider fre-

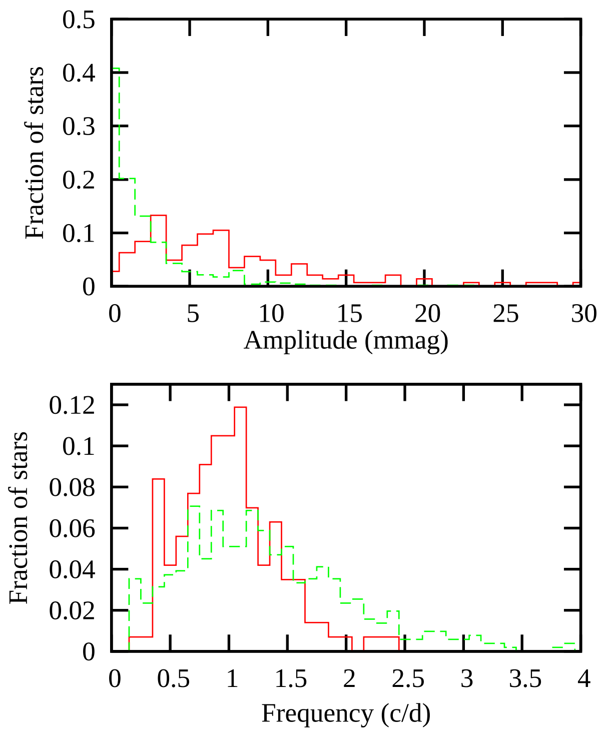

Figure 6. Distributions of in asymmetric (solid, red) curve and symmetric (dashed, green) curve γ Dor stars. The top panel shows the distribution of amplitudes and the bottom panel the distribution of frequencies.

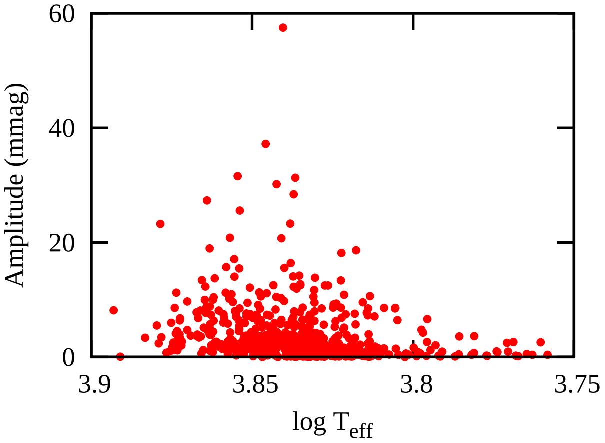

Figure 7. Amplitudes of the dominant periodic component of stars with SYM and ASYM light curves as a function of effective temperature.

quency range in SYM stars may be a result of the spotted stars. It is also possible that the difference in frequency distribution may be related to pulsational driving. Perhaps stars with frequencies close to 1 d^{-1} are driven at higher amplitudes (and therefore tend to be of the ASYM type) than stars with higher frequencies. The amplitudes of both SYM and ASYM types peak at about $\log T_{\rm eff} \approx 3.85$ which is quite close to the blue edge of the γ Dor instability strip (Fig. 7).

5 RELATIONSHIP BETWEEN ROTATION AND PULSATION

We have argued that the stars with ASYM light curves are probably pulsating because the asymmetry is most easily explained as a non-linear effect due to saturation of pulsational driving. This argument cannot be applied to the SYM group. In fact, there is no doubt that many, perhaps a significant fraction, of SYM stars probably do not pulsate at all. In Fig. 8 we show examples of light curves of stars suggestive of migrating star spots (we have called this type SPOTM). These type of light curves are fairly easy to recognize and we have not included them in the SYM class. However, it is easy to imagine that when the differential spot migration rate is small, the light curve would not be recognized as SPOTM but as SYM.

In some stars both pulsation (ASYM light curve) and rotational modulation by starspots may be present. An example of this is KIC 8113425 shown in the bottom panel of Fig. 8. If the traveling feature is interpreted as a starspot, then the pulsation period must be quite close to the rotational period in this star.

To further discuss this topic, it is important to know the relationship between the periods of these presumed γ Dor stars and the rotational period. The best way of obtaining this result is by a statistical investigation between the observed projected rotational velocities, $v_e \sin i$, and the photometric periods. Unfortunately, measurements of $v_e \sin i$ are not available for these stars. However, we can reasonably assume that the rotational velocity distribution for dwarf stars in the *Kepler* field is the same as that for dwarf stars with the same effective temperatures in the general field. Since we do have enough $v_e \sin i$ values for many stars in the general field, such a comparison cam be made.

By definition, there is no dominant frequency in the MULT

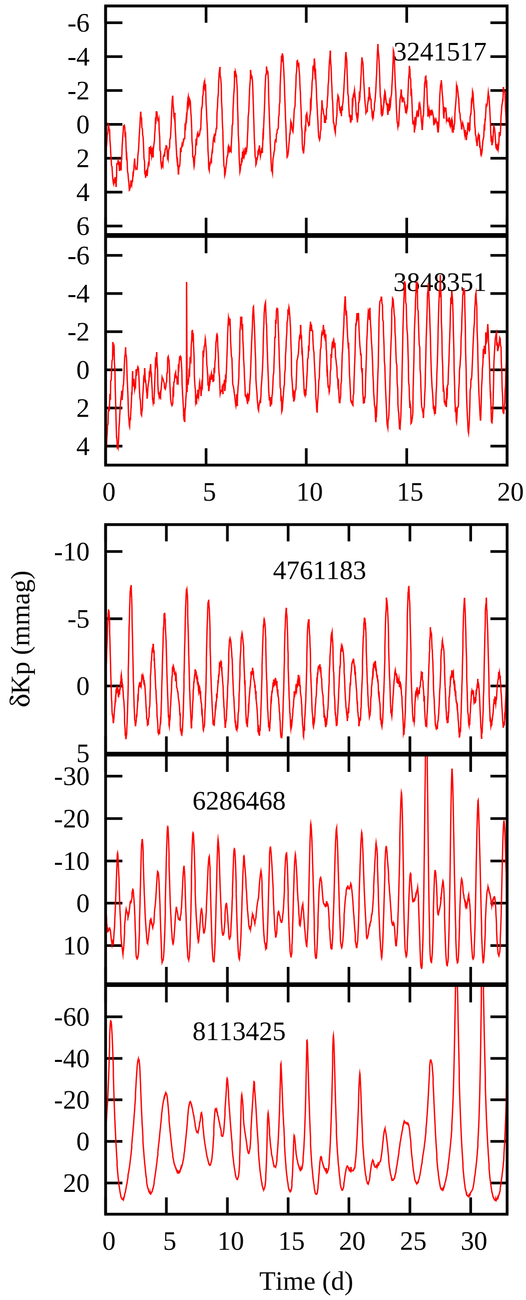

Figure 8. Light curves of symmetric and asymmetric "γ Dor" stars which show evidence of migrating star spots.

group, but we can assume that the dominant frequency in the ASYM and SYM groups is the rotational frequency. Since the KIC provides estimates of the stellar radius, the presumed equatorial equatorial rotational velocity, v_e, can be calculated. If our assumption is correct, the distribution of v_e should match the distribution of equatorial rotational velocities for stars of about the same effective temperatures and luminosity classes. If not, we can use this comparison to estimate the approximate ratio between the pulsation period and rotation period for these stars.

There is a further consideration which needs to be taken into account. This is the fact that periods of γ Dor stars are restricted to a certain range. As already mentioned, the period range from

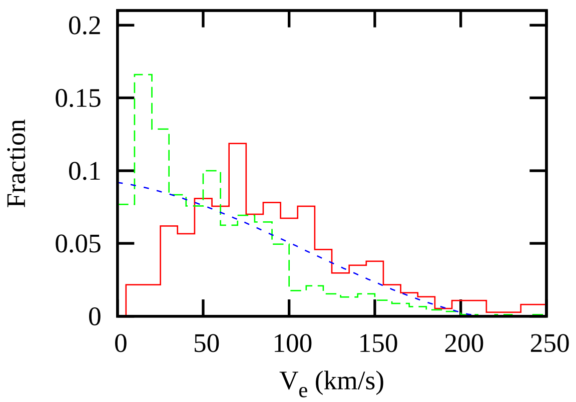

Figure 9. Solid histogram - distribution of equatorial velocities for both types of γ Dor stars in the effective temperature range corresponding to F1–F5 (assuming that the photometric period is the same as the rotation period). Dashed histogram - distribution of $v_e \sin i$ of main sequence F1–F5 stars from the catalogue of Glebocki & Stawikowski (2000). Dashed line - inferred distribution of equatorial velocities from F1–F5 stars.

ground-based studies is between 0.3 and 3.0 d. The typical radius of these stars is about 1.6 R$_\odot$, which means that we may expect the distribution to cover only the range $20 < v_e < 170$ km s^{-1}. The most one can do, therefore, is to determine if there is a match to the equatorial rotational velocity distribution in this restricted range.

The distribution of equatorial rotational velocities can be obtained from the distribution of projected rotational velocities under the assumption that the axes of rotation are randomly distributed. By fitting a simple function to the observed distribution of $v_e \sin i$, the distribution of v_e can be deduced by the method described in Balona (1975). Most of the γ Dor stars have effective temperatures in the range $6500 < T_{\rm eff} < 7000$ K, corresponding to main sequence F1–F5 stars. We can therefore compare the v_e distribution for these stars with the v_e distribution of main sequence F1–F5 stars. We used the catalogue of Glebocki & Stawikowski (2000) to obtain the $v_e \sin i$ distribution for F1–F5 dwarfs in the general field. This distribution can be described by its moments. The distribution of v_e is obtained by applying correction factors to the moments of the $v_e \sin i$ distribution (Balona 1975). The corrected moments are used to calculate a polynomial which describes the v_e distribution.

There are not many stars in the ASYM group, but the v_e distribution is essentially the same as that of the SYM group. We therefore decided to combine the two groups for better statistics. The resulting distribution is shown by the histogram in Fig. 9. Also shown is the histogram of the distribution of $v_e \sin i$ of F1–F5 dwarfs in the general field and the corresponding v_e distribution.

The distribution of v_e for F1–F5 stars is monotonic and decreases steadily from a maximum near zero, while the observed distribution for combined ASYM and SYM stars peaks at about $v_e \approx 70$ km s^{-1}. The tails of the two distributions agree very well, but there is a deficit of low rotational velocities. This is not unexpected, because there are limits to the pulsational frequencies. The mean radius of our sample of ASYM and SYM stars is 1.6 R$_\odot$. An equatorial velocity of 70 km s^{-1} corresponds to a rotational period of 0.73 d or a frequency of 1.375 d^{-1}. The deficit al low v_e could just be due to the fact that γ Dor pulsations are stable for these long periods. The good agreement between the tails of the two distributions is interesting. It suggests that the pulsation and rotation periods must be quite close.

The fact that the dominant frequency in SYM and ASYM stars is so close to the rotational frequency is not too surprising because the typical rotational periods of F stars are of the order of a day or two and overlaps the known range of γ Dor periods. What is interesting is the almost mono-periodic variations in ASYM and SYM stars. It is tempting to relate this to the closeness of the frequency to the rotational frequency. It follows that the dominant spherical harmonic in these stars must be the dipole ($m = \pm 1$) mode, otherwise the frequency would be a multiple of the rotational frequency. Knowing that these stars pulsate predominantly in $m = 1$ modes might offer a start to asteroseismology. Unfortunately, our understanding of pulsation when the pulsation frequency is close to the rotational frequency is very poor.

Finally, we need to understand the difference between the ASYM, SYM classes and the MULT class. Again, this is a difference in degree and there is no absolute dividing line between these classes. The obvious interpretation is that the MULT class represents γ Dor stars with very low rotational velocities (or at least pulsational frequencies considerably higher than the rotational frequency). This would be very easy to test as it just requires comparative $v_e \sin i$ measurements between these groups of stars.

These results also suggest a way of identifying true hybrid γ Dor/δ Sct stars in the *Kepler* database. Since most γ Dor stars appear to be of the SYM and ASYM type, one may look for δ Sct stars with low-frequency beating. It would be important to determine if hybrid stars of this type are confined to a particular region in the HR diagram. If so, this would be a strong argument against pulsation as the cause of most of the low-frequencies in δ Sct stars.

Finally, it may be asked why it is that the SYM and ASYM groups have not previously been identified from ground-based observations. The answer appears to be that the light curves have large gaps which makes such an identification very difficult. However, the almost mono-periodic nature of γ Dor stars in ground-based observations can be deduced from the fact their periodograms are dominated by only one or two frequencies, as found in the *Kepler* γ Dor stars.

6 CONCLUSION

We have completed visual classification of over 10 000 A–F stars in the *Kepler* database mostly from the commissioning period and the first survey period (Q0, Q1). We found stars with very characteristic light curves showing pronounced beating with large variation in maximum brightness and much smaller variation in minimum brightness. These stars with asymmetric light curves seem to belong to a larger sample of stars with similar beating, but more symmetric light curves. A third group of stars shows multiple peaks of comparable amplitude in the low-frequency region strongly suggestive of pulsation. All three types of star fall in the same region of the HR diagram where field γ Dor are to be found. We thus identify them as γ Dor stars. However, our sample of γ Dor stars with symmetric light curves is probably contaminated by spotted stars.

Stars with symmetric and asymmetric light curves have periodograms which show only one or two dominant peaks. We noticed that in ground-based observations of γ Dor stars, the light curves are also mostly dominated by only very few closely-spaced frequencies (see, for example, Cuypers et al. (2009) and the light curve of γ Dor itself, Tarrant et al. (2008)). The characteristic beating of the light curves has not been noticed because it is very difficult to obtain complete light-curve coverage from ground-based observations.

An important question that needs to be asked is why there are so few dominant modes excited in these stars. One possibility is that rotation may play an important role in this regard. To test this idea we tried to match the distribution of equatorial rotational velocities of F1–F5 field main-sequence dwarfs with the equivalent distribution of "equatorial velocities" assuming that the dominant photometric period is exactly equal to the rotation period. With this assumption we find that the tails of the two distributions match quite closely, indicating that our hypothesis cannot be too far from the truth. If the pulsation periods in γ Dor stars are indeed close to their rotational periods, it indicates that the dominant modes have $m = \pm 1$. While knowing this might be an advantage, asteroseismology is severely complicated by the fact that the pulsation periods are so close to the rotational periods.

One needs to ask how the group of γ Dor stars with multiple frequencies of roughly similar amplitudes differs from the other two groups. One possibility is that they are very slow rotators. Spectroscopic observations of several of these stars should enable this question to be answered quite easily.

If these three groups of stars are the true γ Dor stars, it leaves unanswered the nature of low-frequency variations seen in most δ Sct stars. It is possible that the low-frequencies, which occur even in the hottest δ Sct stars are unrelated to pulsation. This question is investigated in Balona (2011). In this case we need to identify the true δ Sct/γ Dor hybrids. Since most γ Dor stars appear to have beats in the light curve, one possibility is to look for similar low-frequency beating in δ Sct stars. If the stars so identified are confined to a narrow region in the HR diagram, it would provide a strong argument against the pulsational nature of low-frequency variation in most δ Sct stars.

ACKNOWLEDGMENTS

The authors wish to thank the *Kepler* team for their generosity in allowing the data to be released to the *Kepler* Asteroseismic Science Consortium (KASC) ahead of public release and for their outstanding efforts which have made these results possible. Funding for the *Kepler* mission is provided by NASA's Science Mission Directorate.

LAB wishes to thank the South African Astronomical Observatory for financial support.

REFERENCES

Balona L. A., 1975, MNRAS, 173, 449

—, 2011, MNRAS, submitted

Balona L. A., Pigulski A., Briquet M., Cuypers J., Daszyńska-Daszkiewicz J., De Cat P., Dukes R. J., Engelbrecht C. A., Frescura F., Garcia R. A., Gutiérrez-Soto J., Handler G., Kawaler S., Lehmann H., Molenda-Żakowicz J., Noels A., Nuspl J., Pricopi D., Roxburgh I., Salmon S., Smith M. A., Suárez J. C., Suran M., Szabó R., Uytterhoeven K., Borucki W. J., Christensen-Dalsgaard J., Kjeldsen H., Koch D., 2011, ArXiv e-prints

Blomme J., Debosscher J., De Ridder J., Aerts C., Gilliland R. L., Christensen-Dalsgaard J., Kjeldsen H., Brown T. M., Borucki W. J., Koch D., Jenkins J. M., Kurtz D. W., Stello D., Stevens I. R., Suran M. D., Derekas A., 2010, ApJ, 713, L204

Bouabid M., Montalbán J., Miglio A., Dupret M., Grigahcène A., Noels A., 2009, in American Institute of Physics Conference Series, Vol. 1170, American Institute of Physics Conference Series, J. A. Guzik & P. A. Bradley, ed., pp. 477–479

Cuypers J., Aerts C., De Cat P., De Ridder J., Goossens K., Schoenaers C., Uytterhoeven K., Acke B., Davignon G., Debosscher J., Decin L., De Meester W., Deroo P., Drummond R., Kolenberg K., Lefever K., Raskin G., Reyniers M., Saesen S., Vandenbussche B., van Malderen R., Verhoelst T., van Winckel H., Waelkens C., 2009, A&A, 499, 967

Debosscher J., Blomme J., Aerts C., De Ridder J., 2011, ArXiv e-prints

Debosscher J., Sarro L. M., López M., Deleuil M., Aerts C., Auvergne M., Baglin A., Baudin F., Chadid M., Charpinet S., Cuypers J., De Ridder J., Garrido R., Hubert A. M., Janot-Pacheco E., Jorda L., Kaiser A., Kallinger T., Kollath Z., Maceroni C., Mathias P., Michel E., Moutou C., Neiner C., Ollivier M., Samadi R., Solano E., Surace C., Vandenbussche B., Weiss W. W., 2009, A&A, 506, 519

Degroote P., Aerts C., Ollivier M., Miglio A., Debosscher J., Cuypers J., Briquet M., Montalbán J., Thoul A., Noels A., De Cat P., Balaguer-Núñez L., Maceroni C., Ribas I., Auvergne M., Baglin A., Deleuil M., Weiss W. W., Jorda L., Baudin F., Samadi R., 2009, A&A, 506, 471

Dupret M., Grigahcène A., Garrido R., Gabriel M., Scuflaire R., 2004, A&A, 414, L17

—, 2005, A&A, 435, 927

Glebocki R., Stawikowski A., 2000, AcA, 50, 509

Grigahcène A., Antoci V., Balona L., Catanzaro G., Daszyńska-Daszkiewicz J., Guzik J. A., Handler G., Houdek G., Kurtz D. W., Marconi M., Monteiro M. J. P. F. G., Moya A., Ripepi V., Suárez J., Uytterhoeven K., Borucki W. J., Brown T. M., Christensen-Dalsgaard J., Gilliland R. L., Jenkins J. M., Kjeldsen H., Koch D., Bernabei S., Bradley P., Breger M., Di Criscienzo M., Dupret M., García R. A., García Hernández A., Jackiewicz J., Kaiser A., Lehmann H., Martín-Ruiz S., Mathias P., Molenda-Żakowicz J., Nemec J. M., Nuspl J., Paparó M., Roth M., Szabó R., Suran M. D., Ventura R., 2010, ApJ, 713, L192

Guzik J. A., Kaye A. B., Bradley P. A., Cox A. N., Neuforge C., 2000, ApJ, 542, L57

Jenkins J. M., Caldwell D. A., Chandrasekaran H., Twicken J. D., Bryson S. T., Quintana E. V., Clarke B. D., Li J., Allen C., Tenenbaum P., Wu H., Klaus T. C., Middour C. K., Cote M. T., McCauliff S., Girouard F. R., Gunter J. P., Wohler B., Sommers J., Hall J. R., Uddin A. K., Wu M. S., Bhavsar P. A., Van Cleve J., Pletcher D. L., Dotson J. A., Haas M. R., Gilliland R. L., Koch D. G., Borucki W. J., 2010, ApJ, 713, L87

Koch D. G., Borucki W. J., Basri G., Batalha N. M., Brown T. M., Caldwell D., Christensen-Dalsgaard J., Cochran W. D., DeVore E., Dunham E. W., Gautier III T. N., Geary J. C., Gilliland R. L., Gould A., Jenkins J., Kondo Y., Latham D. W., Lissauer J. J., Marcy G., Monet D., Sasselov D., Boss A., Brownlee D., Caldwell J., Dupree A. K., Howell S. B., Kjeldsen H., Meibom S., Morrison D., Owen T., Reitsema H., Tarter J., Bryson S. T., Dotson J. L., Gazis P., Haas M. R., Kolodziejczak J., Rowe J. F., Van Cleve J. E., Allen C., Chandrasekaran H., Clarke B. D., Li J., Quintana E. V., Tenenbaum P., Twicken J. D., Wu H., 2010, ArXiv e-prints

Strassmeier K. G., 2010, 2009AARv..17..251S, 390, 1701

Tarrant N. J., Chaplin W. J., Elsworth Y. P., Spreckley S. A., Stevens I. R., 2008, A&A, 492, 167

Warner P. B., Kaye A. B., Guzik J. A., 2003, ApJ, 593, 1049