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Rotational light variations in *Kepler* observations of A-type stars

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ABSTRACT

We analyse the light curves of over 9000 A–F stars in the first public release of *Kepler* data and examine the noise properties in constant or nearly constant stars. For the A stars, we find a correlation between the excess power in certain frequency regions and the effective temperature which may be due to granulation. The majority of A–F stars vary with low frequencies ($<5\,\mathrm{d}^{-1}$) and low amplitudes (40–150 ppm). The low-frequency variation extends to the hottest A-type stars where the typical amplitude is about 40 ppm. We find that about 8 per cent of A8–A0 stars have light curves resembling those usually attributed to starspots in cool stars, including a few exhibiting travelling waves usually interpreted as differentially rotating starspots. A further 20 per cent of A stars have dominant low frequencies which are visible in the periodogram.

If we assume that the dominant low frequency in A–F stars is the rotation frequency, we can calculate the distribution of equatorial rotational velocities given the stellar radii. The resulting distribution matches the distribution of equatorial rotational velocities in field stars of the same spectral type and luminosity class. However, the A8–A0 stars have an excess of slow rotators which can be explained as contamination from horizontal-branch stars. We conclude that the light variations in A-type stars may possibly be due to starspots or other corotating structures and that A-star atmospheres may not be quiescent as previously supposed.

We also analyse low frequencies in *Kepler* A-type δ Sct stars which are too hot to be due to γ Dor pulsations. These do not appear to be due to simple combinations of high-frequency δ Sct modes. Unlike normal A-type stars, the dominant low frequency is close to twice the rotational frequency. In a significant proportion of δ Sct stars there is, in fact, a frequency of smaller amplitude at exactly half the dominant low frequency. There is clearly a quadrupole surface brightness distribution in a significant fraction of these stars, but the amplitudes seem to be too low to be explained as a proximity effect in a binary.

Key words: stars: activity – stars: oscillations – stars: rotation – starspots – stars: variables: general.

1 INTRODUCTION

The advent of high-precision photometry from space is changing our perceptions of stellar variability quite rapidly. The *Most*, *CoRoT* and *Kepler* missions are providing a view at a level of a few micromagnitudes. At this level of precision one may possibly expect interesting behaviour never seen from ground-based observations. One example is the possible detection of starspots in some *CoRoT* B stars (Degroote et al. 2009). Another is the surprising finding that most *Kepler* δ Scuti stars have unexpected low frequencies attributed to γ Doradus pulsations (Grigahcène et al. 2010). These show in the periodogram as a few distinct peaks in the frequency range 0–5 d^{-1}. At a detection threshold of a few micromagnitudes, surface features far too small to be detected from the ground could give rise to rotational modulation. If such features exist and if their lifetimes exceeded a few rotational cycles, they would manifest as low-frequency peaks in the periodograms.

The *Kepler* mission is designed to detect Earth-like planets around stars by the transit method (Koch et al. 2010). The extremely accurate photometry of stars in the *Kepler* data base offers an ideal opportunity to study the variability of main-sequence A–F stars with an unprecedented level of precision and over a long time interval. In a visual inspection of a large number of *Kepler* observations of A–F stars, we noticed that nearly all these stars seem to vary with time scales between a fraction of a day and a few days. It seems that low-frequency variations in these stars are not confined to δ Sct stars, as noted by Grigahcène et al. (2010), but seems to be a general feature of all A–F stars.

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Since there is no known mechanism which can lead to low-frequency pulsations in A stars, the possibility that the variations may be caused by rotational modulation should be investigated. However, no spotted star earlier than about F8 has been detected with certainty. Many A and early F stars possess strong magnetic fields. These are the Ap and Fp stars in which diffusion of elements in a magnetic field has left surface patches of different abundances. The magnetic field in Ap/Fp stars is generally assumed to be a relic of the primordial field that was present in the interstellar gas out of which the stars formed (a fossil field). Magnetic fields generated by dynamo action in the convective core are not expected to penetrate the surface. Moreover, A-type stars do not have significant surface convection so that the mechanism which produces spots on cooler stars is not expected to operate in A-type stars. Thus current thinking is that spots should not be present in normal A-type stars.

Rotational light modulation among four B-type stars has been noted by Briquet et al. (2004) while Makaganiuk et al. (2011) has reported the detection of chemical spots in the binary HgMn star 66 Eridani which lacks a magnetic field. The so-called Maia variables are supposed to be located between the blue edge of the δ Scuti instability strip and the red border of the SPB stars, hence in a domain of the HR diagram where no excitation mechanism for pulsation is yet known. Examples of such stars are rare. A search for Maia variables in *Hipparcos* epoch photometry revealed several hundred candidates (Percy & Wilson 2000). Of these, several dozen stars have been studied in detail and only a handful are possible Maia variables. The possible detection of Maia variables in *CoRoT* observations has also been discussed by Degroote et al. (2009). However, further study is required to determine the effective temperatures and luminosities of these stars and there is no general consensus on whether or not the Maia class really exists.

In this paper we present statistics of the light variations in A-type stars in the *Kepler* public archives. These data clearly show that significant low-frequency variations are present in these stars which require an explanation. In order to select an appropriate sample of stars for study, we classified the variability of over 9000 A–F stars mostly on the basis of the form of the light curve. The classification was done entirely by visual inspection of the light curves and periodograms. We first study the general noise properties of constant (or weakly variable) stars. Using the derived noise properties, we then investigate stars that have been classified into various groups. In particular, we test the idea that the dominant low frequency in these stars might be the rotational frequency by comparing the derived equatorial rotational velocities with those of field stars of the same effective temperature and luminosity. Finally, we turn our attention to the low-frequency variations in A-type δ Sct stars. We examine the idea that many of the low frequencies could be combination frequencies from the δ Sct pulsations. We also compare the dominant low frequency in these stars with the expected frequency of rotation by investigating the distribution of the resulting equatorial rotational velocities.

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 1 month 'thirds'. The data used here is from the 9-d commissioning phase from JD 24554953.54–24554963.24 (Quarter 0 or Q0) and the 33-d first quarter JD 24554964.01–24554997.48 (Quarter 1 or Q1). These data are publicly available. Most of these observations were obtained in long cadence (LC) mode with exposure times of 29.4 min. A smaller number of stars were observed in short cadence (SC) mode with sampling times just under 1 min. The data are available in 'uncalibrated' or 'calibrated' form. The calibrated data suffers from artefacts caused by the processing and is not used here.

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

$T_{\rm eff}$ range	SpType	LC+SC	LC	SC
All		9416	8966	467
$5000 < T_{\rm eff} < 6000$	G9–F9	2330	2285	48
$6000 < T_{\rm eff} < 6500$	F9–F5	782	626	159
$6500 < T_{\rm eff} < 7000$	F5–F1	3500	3414	90
$7000 < T_{\rm eff} < 7500$	F1–A8	1205	1141	69
$7500 < T_{\rm eff} < 10\,000$	A8–A0	1599	1500	101

In preparation for the mission, Sloan Digital Sky Survey (SDSS)-like *griz*, D51 (510 nm) and 2MASS *JHK* photometry was obtained for most stars (Batalha et al. 2010). Effective temperatures, surface gravities and radii derived from this photometry are included in the *Kepler* Input Catalogue (KIC). There are, no doubt, substantial uncertainties in these derived quantities. In this paper the effective temperatures are used only for placing the star within rather wide temperature bins, so the precise value of $T_{\rm eff}$ is not a major factor.

There are 467 stars with $5000 < T_{\rm eff} < 10\,000$ K in the KIC which were observed in SC mode and 8966 stars observed in LC mode. In some cases both SC and LC data are available for the same star. The sample used for visual classification consists of all stars observed in SC mode in this temperature range and all the LC stars with $6500 < T_{\rm eff} < 10\,000$ K. The sample was extended to $T_{\rm eff} = 5000$ 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 successfully corrected in this way (e.g. eclipsing variables) were corrected manually.

To test how low frequencies may be affected by such corrections, we constructed a simulation consisting of the actual times in a LC time sequence of Q0 and Q1 data. We took the light curves of the most constant stars and fitted polynomials separately to Q0 and Q1. The two polynomials do not join smoothly between the two quarters; there is a jump typical of these observations. To these polynomials we added sinusoidal variations comprising 100 frequencies of equal amplitudes and random phases. These frequencies start at 0.1 d^{-1} and are equally spaced by 0.1 d^{-1}. In addition, we added a simulated noise level of 10 μmag. We then applied the code described above to the data and calculated the periodogram of the corrected data. The periodogram recovers all frequencies, including the lowest frequency of 0.1 d^{-1}, although the amplitudes vary slightly from the known simulated value. The same simulation was performed, but this time starting at frequency 0.02 d^{-1} with equal spacing of 0.02 d^{-1}. The periodogram of the corrected data shows the lowest frequency peak at $0.08\,\mathrm{d}^{-1}$. From this exercise, we may deduce that frequencies above about $0.1\,\mathrm{d}^{-1}$ are not affected by the correction procedure, although the amplitudes may be distorted somewhat.

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 any processing. For stars which pulsate at high frequencies, i.e. δ Sct and solar-like oscillations, we relied on the periodograms of uncalibrated data corrected in the way described above. As already mentioned, the majority of stars are clearly variable in the low-frequency regime (i.e. less than $5\,\mathrm{d}^{-1}$). The variability is easily distinguished from instrumental drift which occurs over a longer time-scale.

3 NOISE PROPERTIES OF THE DATA

We begin our study by investigating whether there are any A–F stars in the *Kepler* data base which can be regarded as constant. This is important because we need a benchmark to tell us whether the variations we see in a star are intrinsic to the star or are due to instrumental effects. One intrinsic effect that needs to be considered is granulation noise. It is thought that most A-type stars have non-negligible surface convection, in which case one may expect to see a signature of granulation in these stars. Kallinger & Matthews (2010) point out that the amplitude of the granulation signal is not necessarily correlated with the depth of the convection zone, but it is inversely proportional to the total number of granulation cells on the stellar surface. The average cell size is proportional to the atmospheric pressure scale height. If M and R is the mass and radius, the granulation frequency ν_{gran}, is thought to scale as $\nu_{\mathrm{gran}} \propto MR^{-2}T_{\mathrm{eff}}^{-1/2}$ (Kallinger & Matthews 2010). For stars in the δ Sct instability strip ν_{gran} is in the range 2–7 μHz (20–80 d^{-1}). Kallinger & Matthews (2010) suggest that random noise peaks due to granulation may mimic self-excited modes in the periodogram. They suggest that the huge number of peaks seen in the periodograms of some δ Sct stars observed by *CoRoT* (García Hernández et al. 2009; Poretti et al. 2009) may be better explained by this effect.

The noise level of A stars in the *Kepler* data is flat at high frequencies, rising gently towards zero frequency. We determined the median noise level in the periodogram of the most constant stars in the range $20 < \nu < 80\,\mathrm{d}^{-1}$, the frequency range where granulation noise is expected to peak. We chose to use the median rather than the mean because the median is less affected by large peaks due to noise or a residual pulsation signal. Since even the most constant stars show low-frequency peaks with significant amplitudes, all significant peaks were pre-whitened prior to calculation of the median noise level. These calculations were performed only on stars with SC data.

The median noise level, σ_{M}, depends on the readout noise, shot noise due to the brightness of the star and on the duration of the observations, Δt. If we ignore readout noise, we expect a relationship of the form

$$\log \sigma_{\mathrm{M}} = a + \frac{1}{5}Kp - \frac{1}{2}\log \Delta t,$$

where Kp is the *Kepler* apparent magnitude and a is a constant. By fitting 175 of the least variable stars in the A–F range we find

$$\log \sigma_{\mathrm{M}} = -1.33 + 0.21Kp - 0.47\log \Delta t,$$

where σ_{M} is measured in ppm and Δt in days, confirming the expected relationship. If we define

$$\log \sigma_{\mathrm{corr}} = \log \sigma_{\mathrm{M}} - \frac{1}{5}Kp + \frac{1}{2}\log \Delta t,$$

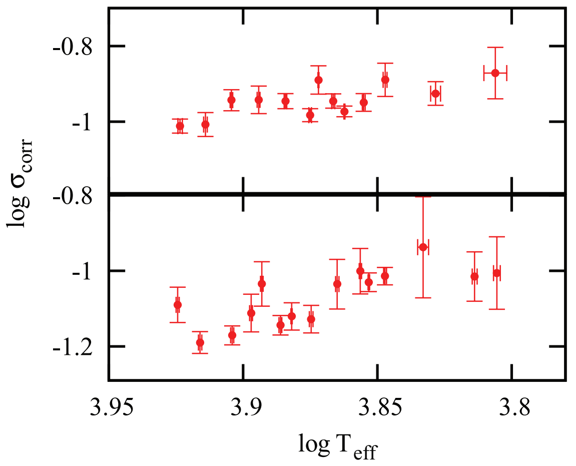

Figure 1. Corrected periodogram noise as a function of effective temperature. Top panel: δ Scuti stars, bottom panel: constant stars.

we find $\log \sigma_{\mathrm{corr}} = -1.108 \pm 0.010$ for $0 < \nu < 20$ and $\log \sigma_{\mathrm{corr}} = -1.187 \pm 0.007$ for $20 < \nu < 80$. This empirical relationship allows the median background power from *Kepler* photometry to be estimated.

Instead of the median, we find that a more useful measure is what we refer to as the ‘grass’ level in the periodogram. This is the typical amplitude of the top of the peaks due to noise. We found that the grass level, σ_{G}, is about 2.5 times the median noise peak height: $\sigma_{\mathrm{G}} = 2.5\sigma_{\mathrm{M}}$. A widely used criterion for deciding whether a certain peak is intrinsic to the star or due to noise is to calculate its signal-to-noise ratio (S/N). If the peak has amplitude A, then $S/N = A/\sigma_{\mathrm{G}}$ and the signal is assumed to be due to noise if S/N is less than a certain value, often taken as 4. In this investigation we used the grass level in calculating S/N.

It is interesting to investigate whether σ_{corr} depends on the effective temperature, T_{eff}, luminosity, $L/\mathrm{L}_{\odot}$ or surface gravity, $\log g$. The only correlation which we can find is an indication that σ_{corr} increases as the temperature decreases. In Fig. 1 we show σ_{corr} for $0 < \nu < 20\,\mathrm{d}^{-1}$ as a function of effective temperature. The diagram for $20 < \nu < 80\,\mathrm{d}^{-1}$ is very similar. Although we initially calculated σ_{corr} for ‘constant’ stars, the same effect is visible in δ Sct stars, as can be seen in the top panel of Fig. 1. In calculating σ_{corr} for δ Sct stars, all significant frequencies were first removed. Note that at the same temperature, σ_{corr} is larger for δ Sct stars: $\log \sigma_{\mathrm{corr}}(\delta\mathrm{Sct}) - \log \sigma_{\mathrm{corr}}(\mathrm{const}) = 0.128 \pm 0.015$. This may be due to unresolved pulsation modes or incomplete removal of peaks in the periodogram.

We conclude from this study that there is a correlation between the noise level and the effective temperature. This might be expected because convection increases for cooler stars and therefore it is reasonable to expect that granulation noise will also increase.

The next question that we want to address is if there is any dependence of the background periodogram noise level with frequency. To do this, we calculated the median noise level in bins of 1 cycle d^{-1} for each star. Each star was assigned a weight inversely proportional to the variance of the overall background and a final curve relating σ_{M}, the weighted median background level to frequency, ν, was obtained. This was applied to periodograms where all significant frequencies are removed. Results are shown in Fig. 2 for constant stars and for δ Sct stars. There is only $1/f$ noise, much of which can presumably be attributed to unresolved low-frequency variations, instrumental or otherwise. The noise is higher in δ Scuti

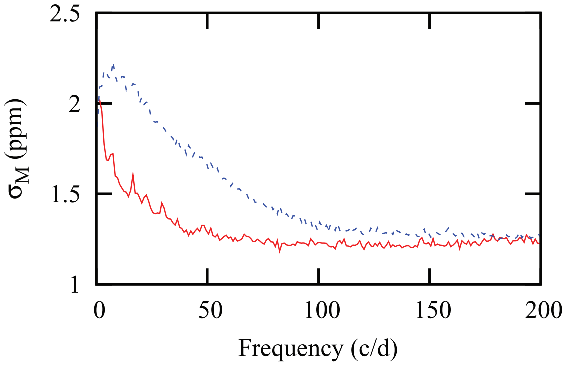

Figure 2. Median periodogram noise (in ppm) as a function of frequency (in cycles d^{-1}) for constant stars (lower solid line) and δ Scuti stars (higher dashed line).

stars, but this is not surprising since these stars probably pulsate in many low-amplitude modes which are below the detection limit.

4 DISTRIBUTION OF LOW FREQUENCIES IN A–F STARS

We would like to know what fraction of A–F stars are variable in the low-frequency range, but we need to qualify what we mean by 'variable' and 'low frequency'. For this purpose, we need to define a representative frequency as there are often several peaks in the low-frequency range. For simplicity, we decided to take the frequency of highest amplitude. Justification for this choice depends on whether or not physically meaningful results are obtained, but in any case we reasoned that if rotational modulation is present, it could not be convincingly demonstrated unless it formed the dominant source of variability.

In determining the variability of a star, we need to keep in mind that faint stars have higher noise levels in the periodogram. The amplitude threshold above which a peak is considered significant is correspondingly higher. To take account of this effect, we need a measure of the noise level as a function of stellar magnitude and duration of the observations. We used the relationships derived in the previous section for this purpose. Given the noise level, we can calculate a threshold amplitude above which frequencies can be considered to be significant. It is common practice to use a threshold amplitude of four times the noise level for this purpose. By noise level, we mean the 'grass' noise level discussed in the previous section. We included the star in the statistics only if the highest amplitude in a given frequency ranges exceeds the threshold amplitude.

We restricted the frequency range to below $5\,\mathrm{d}^{-1}$ since we are only interested in the low-frequency regime. We also restricted the frequency to higher than $0.2\,\mathrm{d}^{-1}$ so as to avoid including frequencies which might be due to instrumental or reduction artefacts. According to the simulation described in the previous section, we could have lowered this limit to about $0.1\,\mathrm{d}^{-1}$, but we used the higher level as an extra precaution. Later in the paper we will be using the dominant low frequency as a possible measure of the rotational frequency of the star. Clipping the lowest frequency to $0.2\,\mathrm{d}^{-1}$ has the effect of undersampling very low rotational velocities, something which one should perhaps bear in mind. For A-type stars the mean radius in the KIC catalogue is about 2.4 $\mathrm{R}_{\odot}$. A rotational frequency of $0.2\,\mathrm{d}^{-1}$ translates into an equatorial velocity of about $10\,\mathrm{km\,s}^{-1}$.

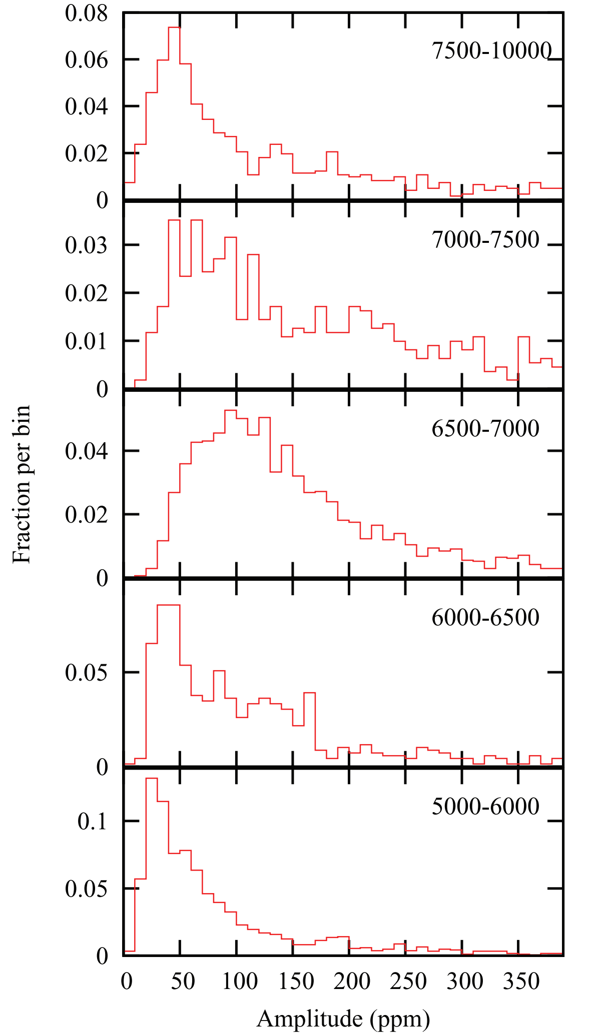

Figure 3. The amplitude distribution of stars which have at least one significant frequency in the range 0.2–5.0 d^{-1}. The labels indicate the range of effective temperature (in K). In all cases there is a very long tail extending to high amplitudes.

Fig. 3 shows the distribution of amplitudes in the frequency range 0.2–5.0 d^{-1} for different temperatures. Given the amplitude A in ppm, the figure shows the fraction of stars with this amplitude in a 10 ppm interval. The figure confirms the impression we obtained from visual inspection of the light curves, i.e. that practically every star is variable in the low-frequency range. These results are robust with respect to the amplitude threshold. Most A8–A0 stars have low-frequency amplitudes of about 40 ppm. The F1–A8 stars peak at about 50–110 ppm while most F5–F1 stars have amplitudes in the range 70–120 ppm. The drop in amplitude for F9–F5 and G9–F9 stars is probably due to the imposition of the lower frequency limit of $0.2\,\mathrm{d}^{-1}$. In these cooler stars, starspot activity is significant, but the rotational frequencies are lower than this limit and therefore excluded in this analysis.

Fig. 4 shows the distribution of frequencies in the range 0.2–5.0 d^{-1}. For the A8–A0 and F1–A8 stars there is a slow drop in numbers of stars with frequency. For the F5–F1 stars, there are very few stars with frequencies greater than $3\,\mathrm{d}^{-1}$. The upper frequency limit decreases until it is not more than about $1\,\mathrm{d}^{-1}$ for the G9–F9 stars. This appears to confirm our suspicion that the drop in typical amplitudes for the cooler stars is mostly due to their exclusion

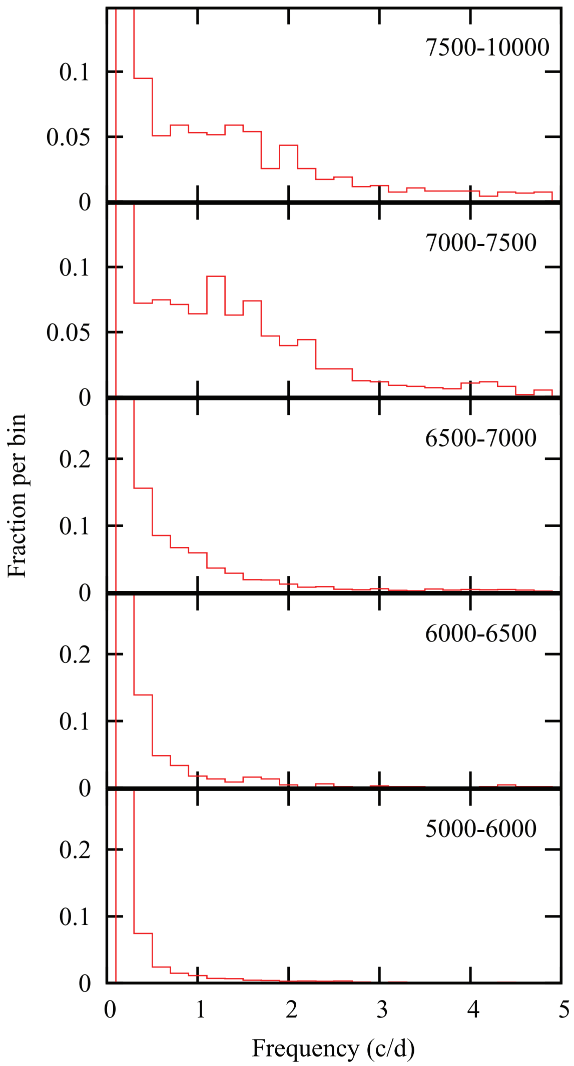

Figure 4. The frequency distribution of stars which have at least one significant frequency in the range 0.2–5.0 d^{-1}. The labels indicate the range of effective temperature (in K). Note that the low-frequency peak value is truncated to show the distribution of higher frequencies more clearly.

from the statistics because their rotational frequencies are less than 0.2 d^{-1}.

5 CLASSIFICATION OF *Kepler* STARS FROM LIGHT CURVES

In order to understand the light curves of *Kepler* stars, it is essential to impose some order, i.e. to classify the variability type from the light curves. It is clearly not possible to determine the physical cause of the variation just from the light curve except in a few obvious cases. For example, one can fairly easily recognize detached eclipsing binaries, RR Lyraes of the RRab type or δ Scuti stars, but even in these cases there is some uncertainty. We know that the among the *Kepler* A-type stars there must be a population of horizontal branch stars. Though it is straightforward to recognize a δ Sct star by its high frequencies, many of these stars could in fact be SX Phe variables.

We stress that classification is done entirely manually by visual inspection of the raw (uncorrected) light curves and the periodogram of the corrected data. The classification scheme we have adopted is based mainly on the morphology of the light curve. The number of stars in various morphological types are shown in Table 2 for different spectral type (i.e. effective temperature) ranges. There are several additional morphological types not listed in the table.

Many stars show almost monoperiodic variations and beating. There are two types in this class, one with asymmetric (ASYM) and the other with symmetric (SYM) light curves. These are assumed to be γ Doradus stars because the vast majority of them fall in the region of γ Dor instability in the HR diagram (Balona et al. 2011b). There is a third type of light curve with multiple low frequencies of comparable amplitude (GDOR). These are also assumed to be γ Dor stars as discussed in Balona et al. (2011b).

For many stars we see a clear single period but with cycle-to-cycle variability quite distinct from the symmetric and asymmetric types discussed above. Sometimes there is a clear double-wave variation. We have called these stars SPOTV to distinguish from an interesting type which is also monoperiodic but with a travelling wave. This type of light curve is normally associated with migrating spots, so we called these stars SPOTM. There is also a class which shows a dominant period or dominant period group, as evidenced by the periodogram, but the light curve is somewhat obscured by other components or irregular variations. In cool stars, this kind of variation would probably be attributed to surface activity of some kind. We have used the term SPOT to describe this type of light curve, although there is no implication that the variability is indeed due to spots.

There are quite a large number of stars where it is not really possible to see variations in the light curve directly because of the low amplitude, but where the periodogram clearly shows a dominant period or a clustered frequency grouping. We have labelled this type of variability as ROT, with no implication that the variability is in fact due to rotation.

Among the contact eclipsing binaries (EB type) are very many peculiar types which have no counterpart in the literature. We have called them EB because of their rather large amplitudes, but the variation may not necessarily be due to eclipses and could be an extension of the SPOTV type.

There are stars which, though not strictly constant, are variable at frequencies below 0.1 d^{-1}, but with very low amplitudes. The variability in this case may not be intrinsic to the star. These we simply call VAR. There certainly are constant stars, recognized by the fact that the periodogram shows no significant peaks at all at any frequency. These stars we classify as CONST. Finally, there is a type which could belong to almost any class, but with such low amplitudes that classification is impossible. In our catalogue there is just a dash in the classification entry.

6 A8–A0 STARS WITH BEATS

In this section we will consider the 1599 A-type *Kepler* stars with $7500 < T_{\rm eff} < 10\,000$ K (equivalent to A8–A0). These stars are of particular interest since the general opinion is that their atmospheres are almost fully radiative and therefore should be quiescent. The *Kepler* data seem to show a different picture.

There are 77 (5 per cent) A8–A0 stars which show periodic variations with beating. These light curves are the same as the symmetric light curves described by Balona et al. (2011b) which we label as SYM. There are only three A-type stars with asymmetric beating light curves (the ASYM type). Because of the pronounced non-linearity of their light curves, and because they fall in the γ Dor instability strip, Balona et al. (2011b) suggest that the ASYM group

Table 2. Numbers of different variables for *Kepler* A-type stars ($7500 < T_{\rm eff} < 10\,000$ K).

Type	Description	G9–F9	F9–F5	F5–F1	F1–A8	A8–A0
–	Unsolved variables	59	10	41	6	32
CONST	Constant stars	20	1	5	2	5
DSCT	δ Sct stars ($\nu > 5\,{\rm d}^{-1}$)	26	10	258	445	515
ASYM	Asymmetric light curves with beats	1	3	65	46	3
SYM	Symmetric light curves with beats	21	45	559	198	77
EA	Detached eclipsing binaries	22	13	44	15	32
EB	Contact eclipsing binaries	33	20	91	44	117
GDOR	γ Dor stars ($\nu < 5\,{\rm d}^{-1}$)	38	2	43	41	2
VAR	Very low amplitude type unknown	740	186	737	194	395
ROT	Dominant low frequency	255	124	558	90	195
RRab	RR Lyraes	2	12	7	4	5
RRc	RR Lyraes	0	1	2	2	1
SPOT	Multiperiodic with dominant frequency	260	144	456	16	39
SPOTM	Clear travelling wave	72	20	16	10	6
SPOTV	Clear dominant period	145	97	389	68	134

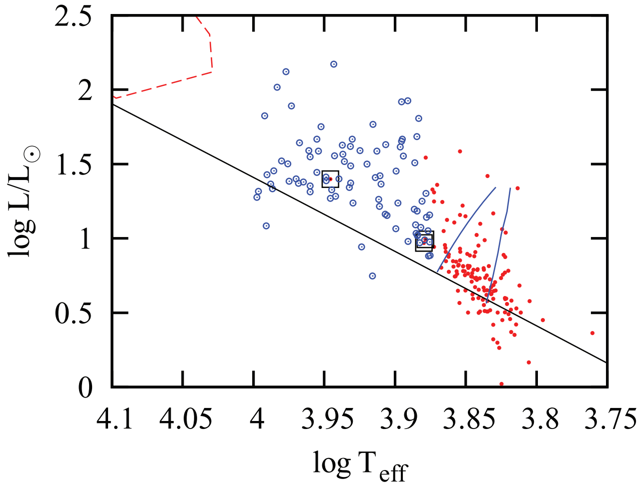

Figure 5. Large filled circles show the location of A-type stars with low-frequency symmetric variations showing beating (type SYM). The three large squares (two overlap) are stars with asymmetric light curves (ASYM). Small filled circles are ASYM stars interpreted as γ Dor stars by Balona et al. (2011b). Also shown are the zero-age main sequence, the red and blue edges of the theoretical γ Dor instability strip and the red edge of the SPB instability strip. These are from Dupret et al. (2004) and Miglio, Montalbán & Dupret (2007) respectively.

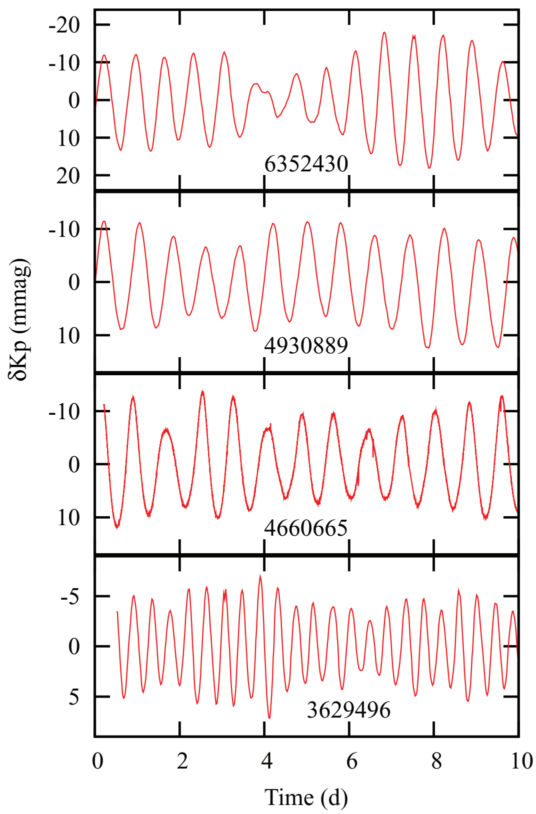

Figure 6. Low-frequency beating in hot A-type stars.

are all γ Dor stars. The SYM group seems to be a lower amplitude extension of the ASYM group, but they are not necessarily all γ Dor stars. Among the F-type stars there are many spotted and active stars with light curves which are also classified as SYM and cannot be distinguished from γ Dor stars (Balona et al. 2011b). Most of the A-type SYM stars have effective temperatures much higher than the blue edge of the γ Dor instability strip, as shown in Fig. 5. It therefore seems reasonable to suppose that these stars are not γ Dor stars but the same as (or related to) the rotationally active F-star SYM group.

The light curves of some of the brighter of these stars are shown in Fig. 6 and the KIC parameters listed in Table 3. The KIC temperatures are unreliable in the B star range (Balona et al. 2011a). In fact, four of these stars, HD 179506, HD 177877, HD 186485 and HD 184939 have B-type classifications. Apart from these, those with known spectral types are classified as A-type. For the four stars with late B-type spectra (assuming that the spectral type classification is correct), we can attribute the variation to SPB pulsation. For some of the cooler star SYM stars, the variation could be ascribed to γ Dor pulsation. However, it is rather unlikely that the effective temperatures or spectral types of most of these stars are in error. The variability of most of the SYM stars, therefore, is not likely to be due to pulsation (or if it is, then the driving mechanism is not known).

We would like to find the physical cause of the variations, but their location in the HR diagram is clearly of no help here. These stars have well-defined frequencies (taken to be the frequency of highest amplitude). It would be important to know how this frequency relates to the rotational frequency of the star. If we knew the projected

Table 3. Parameters from the KIC for hot stars showing beating in their light curves.

KIC	Name	Sp Type	Kep	$T_{\rm eff}$	log g
3629496	HD 177877	B8/9 V	8.334	9796	4.5120
4660665	HD 184629	A2	7.911	7389	3.6630
4930889	HD 184939	B6 V	8.883	9917	4.3380
6352430	HD 179506	B8 V	7.958	9438	4.1750

rotational velocities, $v_{\rm e} \sin i$, we could perform a statistical analysis to ascertain the mean equatorial velocity, $v_{\rm e}$, for this group assuming that the axes are randomly orientated. From the mean radius of the group of stars, we could calculate the typical rotational frequency and compare this with the photometric frequency.

Unfortunately, values of $v_{\rm e} \sin i$ have not been measured for any of these stars. We can make the assumption, however, that the distribution of $v_{\rm e}$ for the *Kepler* stars is the same as the distribution of $v_{\rm e}$ for stars in the general field of the same effective temperature and luminosity class. This assumption seems reasonable, but we need to keep in mind that the *Kepler* A are probably a mixture of main-sequence stars and evolved horizontal-branch stars which are likely to have a different rotational velocity distribution.

To find the distribution of $v_{\rm e} \sin i$ for typical main-sequence A–F stars, we extracted these values for selected spectral-type ranges from the catalogue of Glebocki & Stawikowski (2000). We can represent the distribution of $v_{\rm e} \sin i$ by a simple polynomial by equating the observed and theoretical moments. The moments can be converted to those for the distribution of $v_{\rm e}$ which can also be represented by a polynomial as described by Balona (1975). Of course, we assume that the rotational velocities of stars in the *Kepler* field are similar to those in the general field. This is an assumption, but unless there is a good reason to think that this might not be the case (and we cannot think of one), this seems to us to be entirely reasonable.

We now make the assumption that the dominant frequency in the light curve of these stars is the same as the rotational frequency. We do not necessarily believe this to be the case in general, but what we are trying to do is to find a representative frequency in the low-frequency range. Using the frequency of highest amplitude is one way to do this, though there may be other ways as well. Of course, if our assumption is not justified we will not obtain agreement between the equatorial velocities derived from line broadening measurements and those derived from the dominant frequency and stellar radius. The extracted frequency is confined to the range $0.2 < \nu < 5.0\,{\rm d}^{-1}$ for reasons already described. As already mentioned, the low-frequency limit means that we are restricted to equatorial velocity larger than about $10\,{\rm km\,s}^{-1}$.

Using the extracted frequency, one can estimate $v_{\rm e}$ from the radius in the KIC catalogue and hence derive the distribution of $v_{\rm e}$ from the light curves. There are, of course, errors in the KIC catalogue. If the error in the radius is random, this will lead to a spread in the derived values of $v_{\rm e}$. The result will be a broader distribution, but unless systematic errors are present in the KIC radii, this will not affect the actual mean values in each bin.

If our assumption is correct, this distribution should agree with the distribution of $v_{\rm e}$ obtained from the projected rotational velocities of field stars. If the distributions are different, it will tell us the approximate factor by which the photometric period differs from the rotation period. Such a comparison is shown in Fig. 7. Because the number of stars is relatively small (80 stars), one cannot derive a strong conclusion, but it does appear that the data is consistent

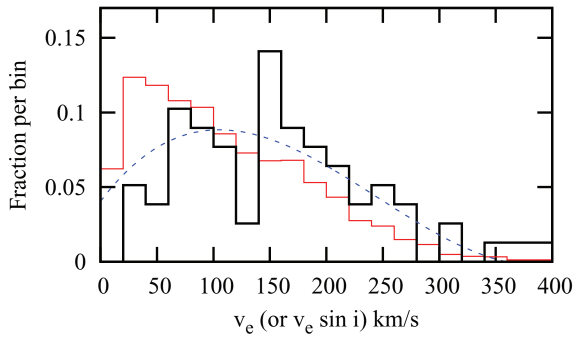

Figure 7. The thin solid line histogram is the distribution of $v_{\rm e} \sin i$ for A8–A0 field dwarfs. The dashed curve is the derived distribution of equatorial velocities, $v_{\rm e}$. The thick solid-line histogram is the distribution of $v_{\rm e}$ for *Kepler* stars with $7500 < T_{\rm eff} < 10\,000$ K and light curves with beats (SYM and ASYM types).

with equality between the photometric and rotational periods. This conclusion is more strongly supported for the cooler stars in Balona et al. (2011b) where the numbers are much larger. There is no obvious difference in appearance between the light curves of these stars and the cooler stars described in Balona et al. (2011b).

As we have already mentioned, there are only three stars of the ASYM class among the A-type stars, whereas the numbers increase greatly for $T_{\rm eff} < 7500$ K. The three stars, KIC 4680338, KIC 7207129 and KIC 10681464, are all rather faint. The light curves of these stars are difficult to understand unless they arise as a saturation mechanism due to pulsation. High-amplitude δ Scuti stars, for example, show this effect in their light curves. This idea is supported by the fact that the ASYM types appear to be the high-amplitude end of the SYM types (Balona et al. 2011b). The three A-type ASYM stars could be γ Dor stars with hot companions or perhaps their effective temperatures could be in error.

Our conclusion from this study of the SYM A-type stars is that the variability could be the result of rotational modulation. In other words, these are the same type of star that one finds among the (late) F- and G-type stars where the variation is attributed to starspots. Alternatively, one may suppose that the variation is not due to the A-star itself, but to a faint cool companion. This is clearly a distinct possibility, though one would have expected no correlation between the light curve frequency and the rotational frequency.

7 LIGHT CURVES OF OTHER A8–A0 STARS

In six A-type stars we clearly see what appears to be a travelling secondary wave in the light curve (the SPOTM type). These stars are listed in Table 4 and their light curves shown in Fig. 8. The light curves can be understood if we postulate starspots which migrate relative to each other (e.g. Lanza et al. 2009). All these stars

Table 4. Parameters from the *Kepler Input Catalogue* for hot stars showing moving features in the light curve (type SPOTM).

KIC	Name	Sp Type	*Kp*	$T_{\rm eff}$	log g
3974751	HD 225660	A	11.440	9265	4.0680
4754121	BD+39 3828	A0	9.626	9162	3.8050
5475664			12.832	7851	4.0750
5481390			13.261	9579	4.4310
6877292			10.469	8950	3.8820
10082844			13.693	9426	4.1290

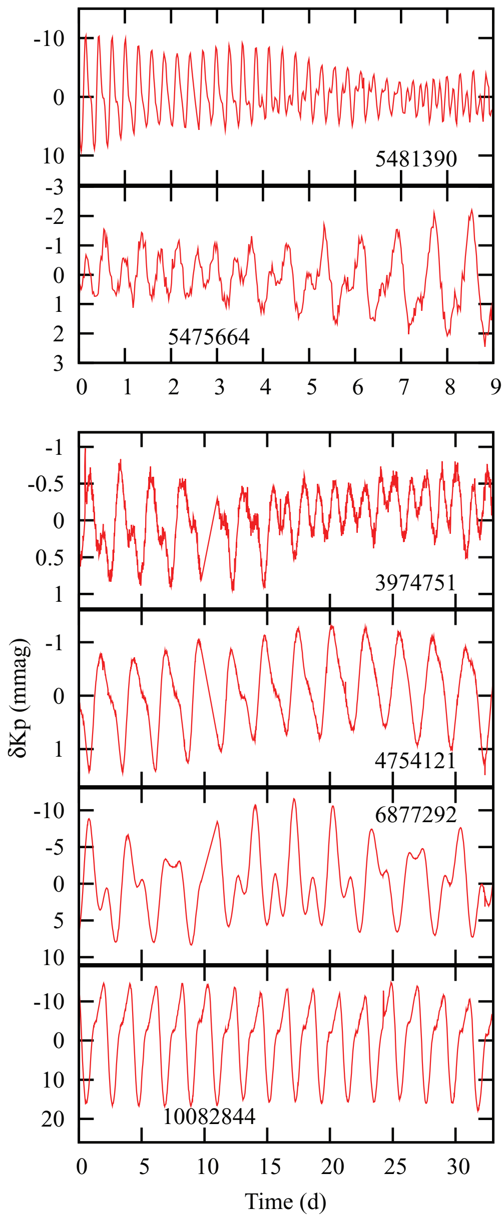

Figure 8. Light curves of A-type stars showing a travelling feature indicative of spots in a differentially rotating star.

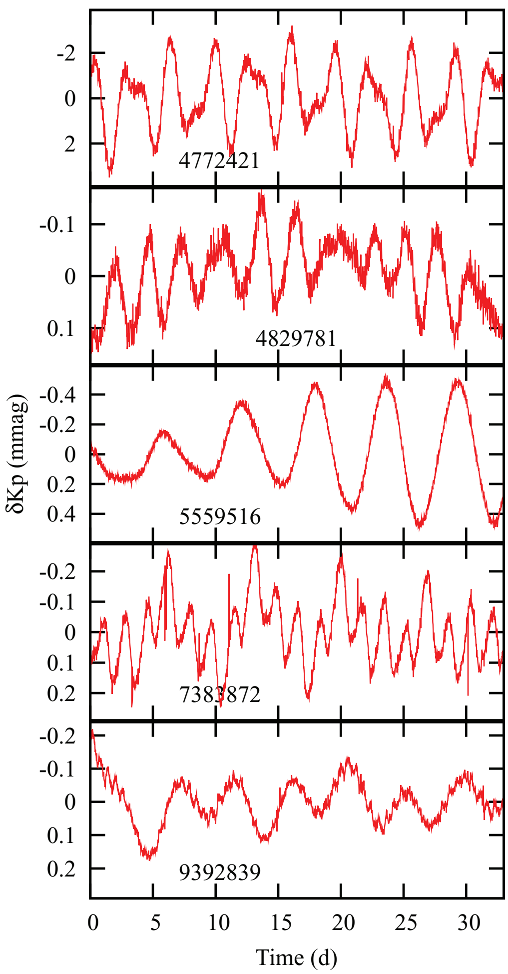

Figure 9. Light curves of A-type stars with a fixed period but with changes similar to what might be expected from starspot activity.

are much hotter than the convective blue edge and therefore not expected to have spots. Alternatively, we could assume the variability to be in a cool companion. It is not possible at this stage to distinguish between the two possibilities.

More frequently, we find light curves which are strictly periodic but where the amplitude changes from cycle to cycle. Sometimes there is a double-wave periodicity. These can be understood if the starspots are fixed but change in size or intensity. There are 134 such light curves among the A-type stars, some examples of which are shown in Fig. 9. Both the SPOTM and SPOTV types are evenly distributed in the HR diagram.

We have seen that the frequencies of stars with light curves showing beats (the SYM group) are statistically the same as their rotational frequencies (Fig. 7). An explanation for these light curves is that they are of rotational origin and are, in effect, the same as the SPOTV class of stars. Analysis shows that stars in the groups SYM, SPOT, SPOTM, SPOTV and ROT all have similar frequency distributions. Under these circumstances it seems reasonable to combine these classes. This gives 444 stars in the A8–A0 range (28 per cent of A stars).

We can repeat the method described in the previous section to determine the relationship between the photometric frequency and the rotational frequency. These results are shown in Fig. 10 for all the A–F stars, not only the A8–A0 stars. We note that, on the whole, there is reasonable agreement between the v_e distribution of field main sequence stars (dashed curve in the figure) and the distribution of v_e obtained from the photometric period of the stars.

There is a problem for the A-type stars (top panel in the figure): there is an excess of stars with low equatorial velocities relative to field stars. We can either conclude that the photometric periods are generally smaller than the rotational period or that one of our assumptions is not correct. We know that the A-type stars are a mixture of main-sequence and horizontal branch stars. The RR Lyraes found in the sample are evidence of this population. Since horizontal branch stars generally rotate more slowly than main-sequence stars, this could account for the abnormal proportion of A8–A0 stars with low equatorial rotational velocities.

With this fairly large sample, one may test the idea that the excess of slow rotators seen in the A stars is due to the inclusion of horizontal-branch (HB) stars. We reason that, on the whole, main-sequence stars are more closely confined to the Galactic plane and therefore closer and brighter. If we restrict our sample to bright

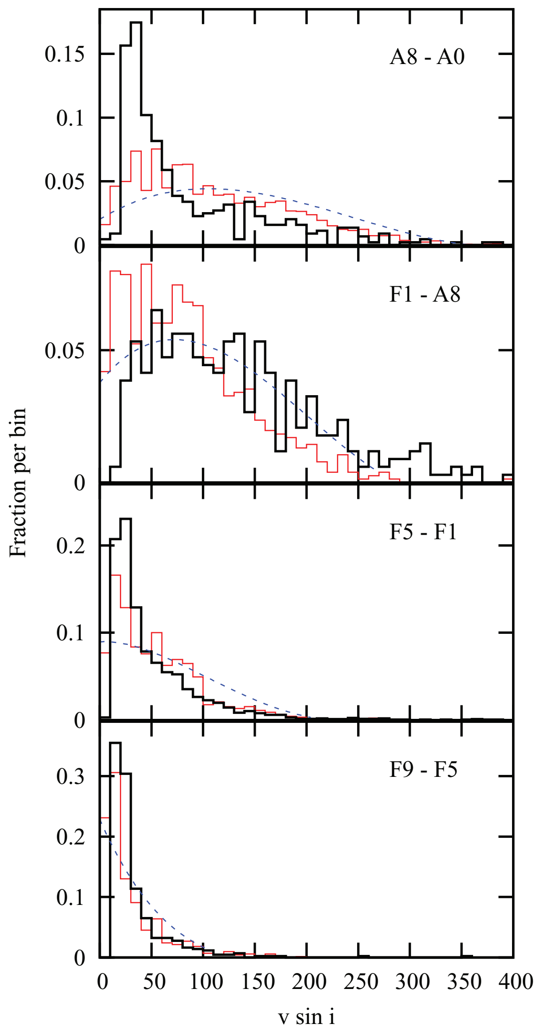

Figure 10. The thin solid histogram is the distribution of projected rotational velocities, $v_e \sin i$, for main sequence field stars in the indicated spectral type range. The dashed curve is the distribution of equatorial velocities, v_e, obtained from the $v_e \sin i$ of these stars assuming random orientation of the rotational axes. The thick solid histogram is the distribution of v_e of combined *Kepler* SYM, ASYM, ROT, SPOT, SPOTM and SPOTV stars in the corresponding effective temperature range.

stars, we can be confident of eliminating many of the HB stars. From the sample of 444 stars in our combined group, we selected stars brighter than magnitude 12. The resulting 228 stars were analysed in the same way. As shown in Fig. 11, the excess of stars with low equatorial velocities is reduced, supporting the idea that this excess is due to HB (hence faint) stars.

Although there is still an excess of slow rotators, the overall shape of the distribution is in good agreement with that of field stars. If rotation were not an important factor, there should be no agreement at all. Fig. 10 shows very clearly that the low frequencies are close to the rotational frequencies for F9–F1 stars, which are not contaminated with HB stars. Since we expect our sample of A stars to contain HB stars, the distribution we obtain is exactly the distribution one would have expected if the low frequencies are the rotational frequencies in both main-sequence and HB stars.

It seems reasonable to conclude that in about 28 per cent of A-type stars there is evidence for rotational modulation. This suggests that starspots or some corotating structures are present in a significant

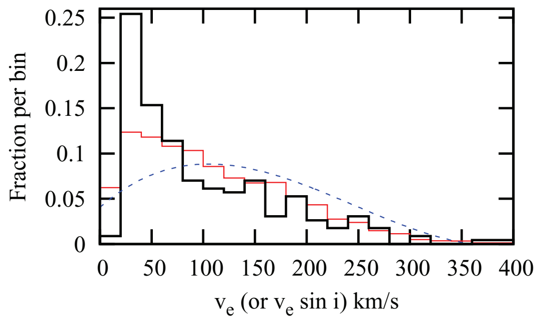

Figure 11. The same as Fig. 10 for A8–A0 stars, but using only stars in the classes SYM, ASYM, SPOT, SPOTM, SPOTV, ROT with $Kp < 12$ mag.

fraction of A stars, contrary to the general view that radiative A-star atmospheres cannot generate starspots.

8 LOW FREQUENCIES IN δ SCT STARS

Low frequencies are nearly always present in *Kepler* observations of δ Sct stars. We would like to know whether these low frequencies are consistent or not with the rotational frequency. We can use the method already described, but this time we need to place a high frequency limit because we do not want to include modes of pulsation in our determination of v_e. If we use a high-frequency limit of $5\,\mathrm{d}^{-1}$, as well as the $0.2\,\mathrm{d}^{-1}$ low-frequency limit, the resulting distribution for 515 (32 per cent) δ Sct stars with $7500 < T_{\rm eff} < 10\,000$ K is shown in Fig. 12 (bottom panel). There is a large excess of stars with low frequencies. If we restrict the sample only to stars brighter than $Kp = 12$, the excess is significantly reduced (top panel). However, in both cases there is clearly no agreement between the dominant low frequency and the typical rotational frequency. We have no reason to suspect that the atmospheres of δ Sct stars are any

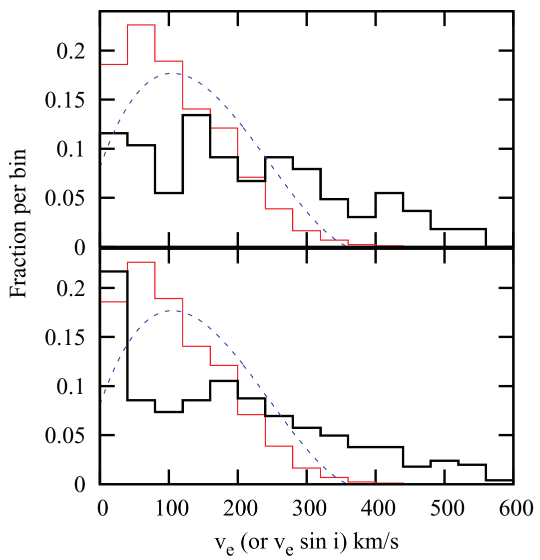

Figure 12. The thin solid histogram is the distribution of projected rotational velocities, $v_e \sin i$, for A8–A0 main sequence field stars. The dashed curve is the distribution of equatorial velocities, v_e, obtained from $v_e \sin i$ assuming random orientation of the rotational axes. The thick solid histogram is the distribution of v_e of *Kepler* δ Sct stars assuming the dominant low frequency is the rotational frequency. Bottom panel: all δ Sct; top panel: δ Sct stars with $Kp < 12$ mag.

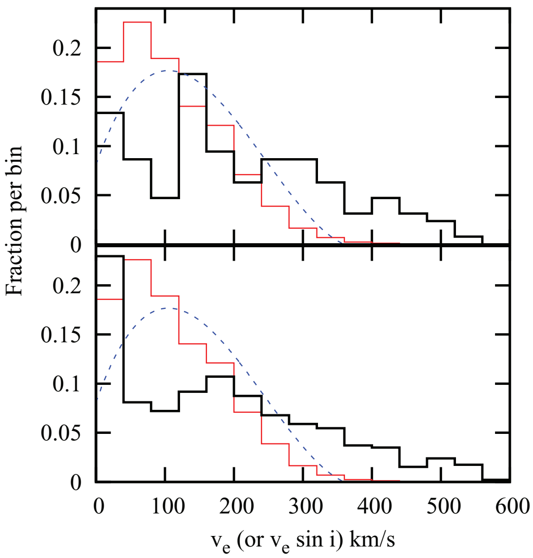

Figure 13. The same as Fig. 12 but omitting stars where the dominant low frequency could be a combination frequency.

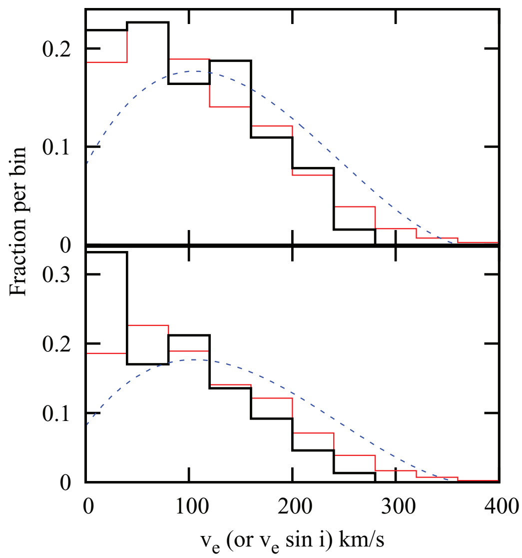

Figure 14. The same as Fig. 13 but halving the dominant low frequency.

different from those of normal A stars. Also, we do not know of any pulsation mechanism which can produce low frequencies for these hot stars. Therefore it seems reasonable to suppose that the dominant low frequency which we extracted could be a combination of two or more high-frequency δ Sct modes, or perhaps a mode moved into the low-frequency range by rotation.

We would like to be able to calculate a distribution free of combination modes. The only way one could identify these modes is by examining all possible combinations of the high δ Sct frequencies and excluding peaks in the low-frequency range which match the combination frequencies. If the amplitude of the combination frequency is A_c and the amplitudes of the parent frequencies are A_1, A_2, the ratio $A_r = A_c/(A_1A_2)$ is usually very small, typically $A_r < 0.01$ (when measured in millimags). Therefore it is not necessary to search through all possible combinations, but only those combinations which give a detectable amplitude for A_c.

We only considered δ Sct stars with $T_{\rm eff} > 7500$ K, since for the cooler stars we may expect γ Dor modes to be present in the low-frequency region. We formed all possible two-frequency combinations from the high-frequency ($\nu > 5\,{\rm d}^{-1}$) modes and selected those that fall in the low-frequency (0.2–5.0 ${\rm d}^{-1}$) range. We then compared the peak of highest amplitude in the low-frequency range with all the combination frequencies. If the frequency is close to a combination frequency, we test the value of A_r. If there is no frequency match within a given tolerance (which we set to 0.05 ${\rm d}^{-1}$), we accept the low-frequency peak as a genuine frequency not due to δ Sct pulsation. We also accept the peak as genuine if $A_r > 0.1$. If the peak is matched by a combination frequency, we test the peak of next-highest amplitude. If this too, is matched by a combination frequency, we ignore the star altogether. Clearly, there are other possibilities that one can attempt and we did, in fact, attempt to use a different frequency tolerance, ignore the restriction on A_r etc., but the results do not differ very much.

The results are shown in the two panels of Fig. 13. The bottom panel shows the supposed v_e distribution for all δ Sct stars excluding combination frequencies (457 stars). The top panel is the same, but including only stars brighter than $Kp = 12$ mag (127 stars). There is almost no improvement, from which we may conclude that combination frequencies are not responsible for the mismatch. In all cases there are too many stars with high 'equatorial velocities'. This result is robust with respect to the exact high- or low-frequency limits, frequency tolerance used in matching a combination frequency, or the maximum value of A_r used to identify a combination frequency. Our final alternative, that the dominant high peak in the low-frequency range is a rotationally shifted mode cannot be tested.

Finally, we would like to know the factor by which the dominant low frequency exceeds the rotational frequency. In Fig. 14 we have arbitrarily halved the value of the dominant frequency. The figure is for stars where combination frequencies are taken into account, but the figures remain almost unchanged if this restriction is removed. We now get good agreement between the v_e distributions for field stars and for δ Sct stars.

The fact that the dominant low frequency appears to be twice the rotational frequency suggests that this is an harmonic and that a peak at the rotational frequency may be present, even if of lower amplitude. Indeed, out of the 515 A-type δ Sct stars, a significant peak could be found within 0.05 ${\rm d}^{-1}$ of the rotational frequency in 124 stars (24 per cent). This is a sizable fraction of the total number of δ Sct stars. The v_e distribution for the 124 stars (assuming half the dominant frequency to be the rotational frequency) is shown in Fig. 15. As can be seen from the figure, there is good agreement between the observed v_e distribution and the v_e distribution for A-type field main sequence stars. This time there is no excess of low frequencies, suggesting that the peak at half the dominant frequency

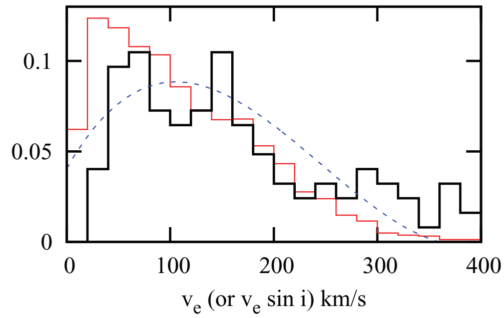

Figure 15. The same as Fig. 13 but for those 124 A-type δ Sct stars having a significant peak at half the dominant low frequency.

is only present in main-sequence δ Sct stars and not in HB δ Sct stars.

The physical cause of the peak at half the dominant low frequency is, of course, of great interest. It is probably either a proximity effect in a binary or a rotational effect. The amplitude of the dominant low frequency in all 124 stars is nearly always less than 1.0 mmag. The peak amplitude occurs at about 100 ppm which is extremely small for a binary proximity effect. It does not seem credible that the binary orbits and masses always conspire to produce such low amplitudes. Moreover, this demands synchronization of rotational period and orbital period, otherwise there is no explanation for the distribution shown in Fig. 15. We conclude, therefore, that this variation results from some kind of rotational modulation, but in that case there must be two nearly equal spots on diametrically opposite sides of the star. We have no explanation why this should be the case and why it exists only in δ Sct stars and not in other A-type stars. Perhaps what we are seeing is some kind of quadrupole sectorial wave with low frequency in the corotating frame. We are not aware of a prediction of such a wave in δ Sct stars.

We conclude that rotation cannot be the only explanation for the low frequencies in hot δ Sct stars and neither can we attribute all these frequencies to combination modes. We found that In δ Sct stars the dominant low frequency is twice the rotational frequency, in strong contrast to other A-type stars. We do not understand why this feature is confined to δ Sct stars. The low amplitudes of the dominant frequencies suggest that this is not a proximity effect in a binary.

9 CONCLUSION

Investigation of the periodograms of a large number of constant or nearly constant A-type stars observed by *Kepler* shows a noise level which gradually decreases towards higher frequencies. For frequencies higher than about 50 d^{-1}, the noise level is almost constant, but it rises exponentially for lower frequencies and is about 60 per cent higher than the base level at very low frequencies.

The idea that convective cells in A-type stars could give rise to granulation noise (Kallinger & Matthews 2010) was investigated. We find a gradual increase in overall stellar noise level with decreasing effective temperature. We interpret this to indicate the increasing importance of granulation for the cooler A stars.

We have compiled a catalogue of over 9000 stars in the first *Kepler* public release and have classified each star by the morphology of its light curve and information from the periodogram. Visual inspection of the light curves of 1599 A-type stars observed by *Kepler* shows low-frequency variability in many stars which cannot be ascribed to instrumental causes. These variations are rather complex to be attributed to a binary effect. Moreover, the amplitudes are often too low and the stars too numerous to be accounted by proximity effects of a binary. We find that the low frequencies ($0.2 < \nu < 5.0\,\mathrm{d}^{-1}$) in most A-type stars have typical amplitudes of about 40 ppm. This amplitude increases gradually for cooler stars, reaching about 100 ppm for the F5–F1 stars.

Balona et al. (2011b) discovered many stars with asymmetrical, beating, light curves which fall in the region of the HR diagram where γ Dor stars are expected. These stars appear to be the high-amplitude counterparts of a group with symmetrical light curves, but these are easily confused with stars whose variation is due to starspots. We find 77 stars of the symmetric class are in the A8–A0 spectral type region that are evenly spread in the HR diagram. Only three stars of the asymmetric class are A-type stars. Since there is no pulsation mechanism which can account for the low frequencies in these stars, we assume that they are just the hotter counterparts of the spotted F-type stars. To test this idea, we compared the equatorial rotational velocities derived from the photometric periods and estimated radii (assuming that the photometric period is the same as the rotational period) to the equatorial rotational velocities of field stars of the same spectral type and luminosity class. The agreement between the distributions is consistent with the photometric period being equal to the rotation period. Another explanation is that the variation is caused by a cool companion and not in the A star itself. This is an appealing idea, but in that case one should not find a correlation between the photometric period and the rotational period as we seem to do.

Among the A-type stars we find a few stars showing a travelling wave identical to that found in cool stars and attributed to migrating starspots. A much larger number of stars show periodic variations with a dominant period but changes in shape and amplitude also suggestive of starspots. There are also a great many stars where the amplitudes are too low to distinguish the variations, but where the periodogram shows a clear dominating period. The distribution of equatorial velocities for all these stars closely resemble those of field stars, but with an excess of slow rotators in the A-type stars. When we confine our sample to the brighter A-type stars, this excess is reduced. We attribute the excess of low equatorial rotational velocities to a population of horizontal-branch A-type stars with low rotational velocities relative to main-sequence A stars.

These results can be understood if the low-frequency variability in A-type stars is due to rotational modulation. This may be a result of starspots or corotating structures. Similar light curves have been observed by *CoRoT* among late B-type stars which have likewise been attributed to star spots (Degroote et al. 2009). If this is the case, the idea that A-type atmospheres are quiescent needs to be revised.

We expected that the problem of the low frequencies in hot, A-type δ Sct stars would be resolved in a similar way as due to rotation. We were surprised to find that under this assumption one obtains a long tail of high equatorial rotational velocities which does not match the typical distribution for stars of the same effective temperature and luminosity class. We tested the idea that the distribution was being affected by low-frequency combinations of high-frequency modes, but no significant difference was found. However, we do find good agreement if the dominant low frequency is twice the rotational frequency. Closer inspection shows that about 24 per cent of A-type δ Sct stars have frequencies at half the dominant low frequency. The amplitudes of the dominant low frequencies are very low (typically only about 100 ppm) and often there are many other low frequencies which cannot easily be interpreted as a proximity effect in a binary. The fact that the dominant low frequency in δ Sct is twice the rotational frequency and not just the rotational frequency as in other A-type stars is not understood.

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REFERENCES

Balona L. A., 1975, MNRAS, 173, 449
Balona L. A. et al., 2011a, MNRAS, 413, 2403
Balona L. A., Guzik J. A., Uytterhoeven K., Smith J., Tenenbaum P., Twicken J. D., 2011b, MNRAS, in press
Batalha N. M. et al., 2010, ApJ, 713, L109
Briquet M., Aerts C., Lüftinger T., De Cat P., Piskunov N. E., Scuflaire R., 2004, A&A, 413, 273
Degroote P. et al., 2009, A&A, 506, 471
Dupret M., Grigahcène A., Garrido R., Gabriel M., Scuflaire R., 2004, A&A, 414, L17
García Hernández A. et al., 2009, A&A, 506, 79
Glebocki R., Stawikowski A., 2000, Acta Astron., 50, 509
Grigahcène A. et al., 2010, ApJ, 713, L192
Kallinger T., Matthews J. M., 2010, ApJ, 711, L35
Koch D. G. et al., 2010, ApJ, 713, L79
Lanza A. F. et al., 2009, A&A, 493, 193
Makaganiuk V. et al., 2011, A&A, 529, 160
Miglio A., Montalbán J., Dupret M., 2007, Comm. Asteroseismol., 151, 48
Percy J. R., Wilson J. B., 2000, PASP, 112, 846
Poretti E. et al., 2009, A&A, 506, 85

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