

ROTATION IN THE PLEIADES WITH K2: II. MULTI-FREQUENCY STARS

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ABSTRACT

We use K2 to continue the exploration of the distribution of rotation periods in Pleiades that we began in Paper I. We have discovered complicated multi-period behavior in Pleiades stars using these K2 data, and we have grouped them into categories, which are the focal part of this paper. About 24% of the sample has multiple, real frequencies in the periodogram, sometimes manifesting as obvious beating in the light curves. Those having complex and/or structured periodogram peaks, unresolved multiple periods, and resolved close multiple periods are likely due to spot/spot group evolution and/or latitudinal differential rotation; these largely compose the slowly rotating sequence in P vs. $(V - K_s)_0$ identified in Paper I. The fast sequence in P vs. $(V - K_s)_0$ is dominated by single-period stars; these are likely to be rotating as solid bodies. Paper III continues the discussion, speculating about the origin and evolution of the period distribution in the Pleiades.

1. INTRODUCTION

Ultra-high precision photometry can reveal a wealth of multi-frequency behavior, and indeed, one of the original goals of the Kepler mission was to investigate asteroseismology (*e.g.*, Metcalfe et al. 2009) and stellar cycles, including differential rotation (*e.g.*, Karoff et al. 2009). Rotation rates and timescales for stellar cycles are thought to be a function of age of the star. The original Kepler field, however, had no clusters younger than 1 Gyr. With the repurposed K2 mission (Howell et al. 2014) comes the opportunity to study clusters of a much wider range of ages, with the potential to constrain measures of, say, surface differential rotation at much younger ages.

The Pleiades is populous (over 1000 members, *e.g.*, Bouy et al. 2015), relatively young (125 Myr; Stauffer et al.

1998a), and nearby (136 pc; Melis et al. 2014). As such, it provides a nearly ideal laboratory for studying rotation of young stars, including surface differential rotation and spot or spot group evolution. These stars are old enough to have completed all of their pre-main sequence accretion and most of their pre-main sequence contraction, but they are still young enough to be rotating quickly enough that there are at least 6-7 complete rotations over a K2 campaign (~ 70 d long), and their spots/spot groups are large enough to produce brightness variations easily detectable by K2 ($\gtrsim 0.003$ mag).

Rebull et al. (2016), Paper I, presented the K2 Pleiades data and reduction, membership selection, and our general results. About 92% of the members in our sample have at least one measured spot-modulated rotation period. The overall relationship between P and $(V - K_s)_0$ follows the overall trends found in other Pleiades studies. There is a slowly rotating sequence for $1.1 \lesssim (V - K_s)_0 \lesssim 3.7$ ($2 \lesssim P \lesssim 11$ d), and a primarily rapidly rotating population for $(V - K_s)_0 \gtrsim 5.0$ ($0.1 \lesssim P \lesssim 2$ d). There is a region in which there seems to be a disorganized relationship between P and $(V - K_s)_0$ between $3.7 \lesssim (V - K_s)_0 \lesssim 5.0$ ($0.2 \lesssim P \lesssim 15$ d).

In the analysis conducted as part of Paper I, we noticed that a significant fraction of the periodograms, $\sim 30\%$, had additional, significant peaks in the periodogram. In these cases, the false alarm probability (FAP) for the additional peaks was just as low as that for the main peak, often calculated to be exactly 0. The K2 light curves (LCs) are so exquisite that when subsidiary peaks appear as significant, it is worth investigating, which is the motivation for this paper.

In this paper, we focus on the diversity of multi-frequency periodograms and LCs we find in these K2 Pleiades data. Section 2 summarizes the key points of the observations and data reduction from Paper I. Section 3 describes the several categories of LCs and periodogram structures that we found in the K2 data. The simplest division of the LCs and periodograms is into single- and multi-period stars; the distributions of these broad categories are discussed in Section 4. However, we have many more than just two categories of LCs and periodogram structures; Section 5 looks at where these various categories of objects fall. Section 6 looks at the distribution of period differences. Section 7 summarizes our main results. This is the second of three papers focused on rotation periods in the Pleiades. Stauffer et al. (2016), Paper III, continues the discussion of these Pleiades results, focusing on the physical origins of the P distribution.

2. OBSERVATIONS AND METHODS

The observations and methods are discussed in detail in Paper I. Here, we simply summarize the main points:

- Members of the Pleiades were observed in K2 campaign 4, which lasted for 72d. All of the stars in this sample were observed in the long-cadence (~ 30 min exposure) mode.
- We looked for periods using the Lomb-Scargle (LS; Scargle 1982) approach.
- For stars of the mass range considered here, the periods that we measure are, by and large, star spot-modulated rotation periods. Spot modulation is the simplest explanation for sinusoidal (or sinusoidal-like) variations where there are changes over an entire orbital phase.
- We assembled a catalog of literature data for our targets. The most important values obtained from this search are $(V - K_s)_0$ (measured or inferred; see Paper I) and membership (see Paper I). Cross-IDs between the EPIC number, RA/Dec, and common literature names are in Paper I.
- Out of the 1020 LCs of candidate Pleiades members from which we started, there are 775 high-confidence members, with 51 more lower-confidence members (for a total of 826 members). Table 2 includes these numbers.
- Out of those 775 (best members), 716 (92.4%) have at least one measured period that we believe in the overwhelming majority of cases to be a rotation period and due to star spots. Including the lower confidence members, 759/826 (91.9%) have at least one measured period.
- The period distribution is strongly peaked at $P < 1$ d with typical amplitudes of ~ 0.03 mag.

Table 1 includes the supporting data from Paper I, plus, for each star, its LC categories as introduced in this paper.

As stated above, what drove us to investigate the multi-period behavior was the presence of additional, significant (low FAP) peaks in the periodogram. To first order, we took the periods in order of peak strength (and thus significance); all other things being equal, the highest peak is what we took to be the primary period, P_1 , the second highest peak is what we took to be the secondary peak, P_2 , etc. However, in some cases, we had to overrule that ordering of the periods (see, *e.g.*, §3.1).

Table 1. Contents of Table: Periods, Supporting Data, and Light Curve Categories for Periodic Pleiades

Label	Contents
EPIC	Number in the Ecliptic Plane Input Catalog (EPIC) for K2
coord	Right ascension and declination (J2000) for target
Vmag	V magnitude (in Vega mags), if observed
Kmag	K_s magnitude (in Vega mags), if observed
vmk0	$(V - K_s)_0$ – dereddened $V - K_s$, directly observed (if V and K_s exist) or inferred (see text)
P1	Primary period, in days (taken to be rotation period)
P2	Secondary period, in days
P3	Tertiary period, in days
P4	Quaternary period, in days
ampl	Amplitude, in magnitudes, of the 10th to the 90th percentile
memb	membership indicator: Best, OK, or NM
single/multi-P	indicator of whether single or multi-period star
dd	indicator of whether or not it is a double-dip LC
ddmoving	indicator of whether or not it is a moving double-dip LC
shch	indicator of whether or not it is a shape changer
beat	indicator of whether or not the full LC has beating visible
cpeak	indicator of whether or not the power spectrum has a complex, structured peak and/or has a wide peak
resclose	indicator of whether or not there are resolved close periods in the power spectrum
resdist	indicator of whether or not there are resolved distant periods in the power spectrum
pulsator	indicator of whether or not the power spectrum and period suggest that this is a δ Scuti pulsator
cloud	indicator of whether or not the phased light curve has narrow, angular dips

Table 2. Star/Light Curve/Periodogram Categories^a

Name	Number	Frac. of sample ^b	Frac. of periodic sample ^c	Empirical properties	Possible Physical Interpretation
Initial sample (see Paper I)	1020	All K2 LCs of candidate Pleiades members	...
Best members (see Paper I)	775	Highest-confidence (our determination) Pleiades members with K2 light curves, and neither too bright nor too faint ($6 < K_s < 14.5$)	...
OK members (see Paper I)	51	Lower-confidence (our determination) Pleiades members with K2 light curves, and neither too bright nor too faint ($6 < K_s < 14.5$)	...
The sample, a.k.a. the sample of members	826	1.00	...	The set of all high-confidence ('best') plus lower-confidence ('ok') members that are neither too bright nor too faint ($6 < K_s < 14.5$)	...
The periodic sample	759	0.92	1.00	The subset of all high-confidence ('best') plus lower-confidence ('ok') members that are neither too bright nor too faint ($6 < K_s < 14.5$) and are found to be periodic by us in these K2 data	...
Single frequency	559	0.68	0.74	The star has just one detectable period. Could be sinusoid or other shapes, but there is just one detectable period.	single spot/spot group rotating into and out of view
Double-dipped (or double-humped)	107	0.13	0.14	There is a double-dipped (or double-humped) structure in the phased LC, <i>and</i> the power spectrum has a substantial amount of power in the harmonic ($P/2$) compared to the main P .	two spot/spot groups, well separated in longitude, rotating into and out of view
Moving double-dip	31	0.038	0.041	<i>(Effectively a subcategory of both double-dip and shape changers.)</i> There is a double-dipped (or double-humped) structure in the phased LC, <i>and</i> often the power spectrum has a substantial amount of power in the harmonic ($P/2$) compared to the main P , <i>and</i> one can see by eye that one structure in the LC is moving with respect to the other structure over the campaign.	spot/spot group evolution and/or latitudinal differential rotation
Shape-changer	114	0.14	0.15	Shape of the light curve changes over the campaign, but not enough such that a separate period can be derived. Usually, these are single-period stars.	latitudinal differential rotation and/or spot/spot group evolution
Orbiting clouds?	5	0.0061	0.0066	The phased light curves show shallow, angular dips which cover a relatively small portion of the total phase. (NB: one more is formally a NM, for a total of 6)	orbiting clouds or debris??
Multi-frequency	200	0.24	0.26	More than one frequency is measured, or apparent by eye (in the periodogram or the LC itself) even if specific value cannot be determined.	spot/spot group evolution and/or latitudinal differential rotation and/or binarity
Beater	135	0.16	0.18	Light curve appears to have beating signatures by eye (<i>e.g.</i> , changing envelope over the campaign).	spot/spot group evolution and/or latitudinal differential rotation
Complex peak	89	0.11	0.12	Peak in power spectrum is structured (multi-component) or wider than expected for that period.	latitudinal differential rotation and/or spot/spot group evolution
Resolved multi-period, close	126	0.15	0.17	Well-resolved, very narrow peaks in the power spectrum and both periods are real. The periods are very close together by the $\Delta P/P$ metric.	latitudinal differential rotation and/or spot/spot group evolution in most cases; binarity in other cases
Resolved multi-period, distant	37	0.045	0.049	Well-resolved, very narrow peaks in the power spectrum and both periods are real. The periods are <i>NOT</i> very close together by the $\Delta P/P$ metric.	binarity
Pulsator	8	0.0097	0.011	"Forest" of short-period peaks in the periodogram.	Pulsation (δ Scuti)

^a The first half of this table includes numbers discussed in detail in Paper I. The second half of this table is a high-level summary of the categories discussed in detail in Sec. 3. Please see the text for a much longer discussion of properties and interpretation.

^b Fraction out of 'the sample', *e.g.*, 826. Stars can belong to more than one category, so the fractions do not add to 1.

^c Fraction out of 'the periodic sample', *e.g.*, 759. Stars can belong to more than one category, so the fractions do not add to 1.

3. EMPIRICAL STRUCTURES IN THE LIGHT CURVES AND POWER SPECTRA

While inspecting the power spectra of the ensemble of K2 LCs, about 60% of the ensemble had properties as found in Fig. 2 of Paper I, where there was just one sinusoidal periodic signal, and it was unambiguously periodic (very low FAP), with just one frequency. However, we noted that about 30% of the sample potentially had more than one significant period in the power spectrum, where the FAP was just as low for these additional peaks. We phased the LCs at these additional peaks, and in many cases, the phased LC is just as convincing as the LC phased at the main peak.

We noticed patterns in the power spectra (and/or the original and phased LCs), which enabled us to group these multi-period objects into categories, which we discuss in this section, and summarize in Table 2. Note that objects can simultaneously belong to more than one of these categories. We conclude this section by discussing the ensemble incidence rate of multi-period LCs. For all of the discussion here, ‘the sample’ is members of the right brightness range, as described in Paper I and Table 2.

For those stars where we can distinguish multiple plausible frequencies, we have included in Table 1 the secondary (and tertiary or even quaternary in some cases) periods. The first period that is listed is the strongest period and/or the one we believe to be the rotation rate of the star. Some of these stars are known or inferred binaries; in these cases, the period should most often be that of the primary. If they are unresolved multiples, we cannot assign directly measured K_s or $(V - K_s)_0$ to the companion, so these companions do not appear as separate stars in our analysis (here or in Paper I or III).

Finally, for completeness, we note that in a few cases, it was difficult to determine if a subsidiary peak in the periodogram was a harmonic (usually half the true P) or an independent period. Our primary discriminant was by eye – if the LC phased to a subsidiary peak had characteristics of a harmonic (*e.g.*, a wide distribution of fluxes at most phases and a ‘criss-cross’ appearance of the phased LC), then we took it to be a harmonic and did not include it as an independent period derived from our data. For most of these cases where the by-eye assessment identified the subsidiary peak as a harmonic, the ratio of the true P to the harmonic was very close to 2. Based on that, even if the phased LC did not obviously appear to be a harmonic, but the ratio of the periods was within 3% of 2 ($1.97 < P_1/P_2 < 2.03$), then we took the periods to be, in fact, harmonics, and did not retain the shorter P as an independent, second period.

3.1. Double-dipped LCs

For sinusoidal, single-frequency LCs, as seen in Fig. 2 of Paper I, if there is a secondary peak in the power spectrum, it is very weak relative to the main peak. However, many of the LCs have double-dipped (or double-humped) structure in their phased LCs¹. When the two dips are of comparable depth and fraction of the orbital phase, there is enough power in the $P/2$ harmonic that it appears with comparable strength in the periodogram. Taken at face value, then, such a power spectrum makes the star appear to have (at least) two significant periods; see Figure 1. Sometimes the $P/2$ peak is of comparable strength to the P peak, and sometimes, the $P/2$ harmonic is actually the dominant peak (perhaps by a considerable margin) in the periodogram. (Recall that the LS approach is fitting sinusoids, so the relative strength of the peaks is related to the strength of the single sinusoidal nature of the periodicity.) For these cases, visual inspection reveals that the true rotation period is actually P and not $P/2$, as shown in Fig. 1. The peaks are typically very narrow, suggesting a limited range of frequencies found around the period (and $P/2$) during the campaign. About 14% of the sample (and 15% of the periodic sample) have this kind of power spectrum and phased LC shape.

We identified the double-dip LC types by eye, but we considered both the properties of the phased LC shape and the structures of the periodogram. To be in the double-dip category, there has to be double-dip (or -hump) structures in the phased LC as well as substantial power in the nominally subsidiary peak $P_{\text{true}}/2$. (In other words, the periodogram has to look like it has 2 significant periods, but in reality only one of the pair is a viable period.²) Therefore, we do not include in this category those LCs that have multiple dips/humps in the phased LC where the ratio of the peak power values for the correct P and the first subsidiary peak is large. A phased LC with two (or more) dips of very different shape or relative duration will result in the power spectrum correctly identifying the right period, with little

¹ McQuillen et al. (2013) use this same terminology for similar LCs.

² This feature, where the periodogram looks like it has two significant periods but in reality has only one real period, accounts for the apparent discrepancies in some of the sample fractions given. At the end of the analysis: (a) 59% have one and only one period and a \sim sinusoidal LC. (b) 68% have one and only one period, consisting of both the \sim sinusoidal LC and those double-dip LCs that look like they have 2 significant periods but in reality have only one. (c) When approaching the analysis of the LCs with *potentially* more than one significant peak in the periodogram, therefore, we include all the stars that in the end legitimately have more than one period, plus the double-dip stars that only appear to have more than one period (noting that some double-dip stars do legitimately have more than one real period). Therefore, 33% of the sample have *potentially* more than one significant peak in the periodogram, which then decreases to 24% actually having multiple frequencies in the end. (8% are not periodic at all.)

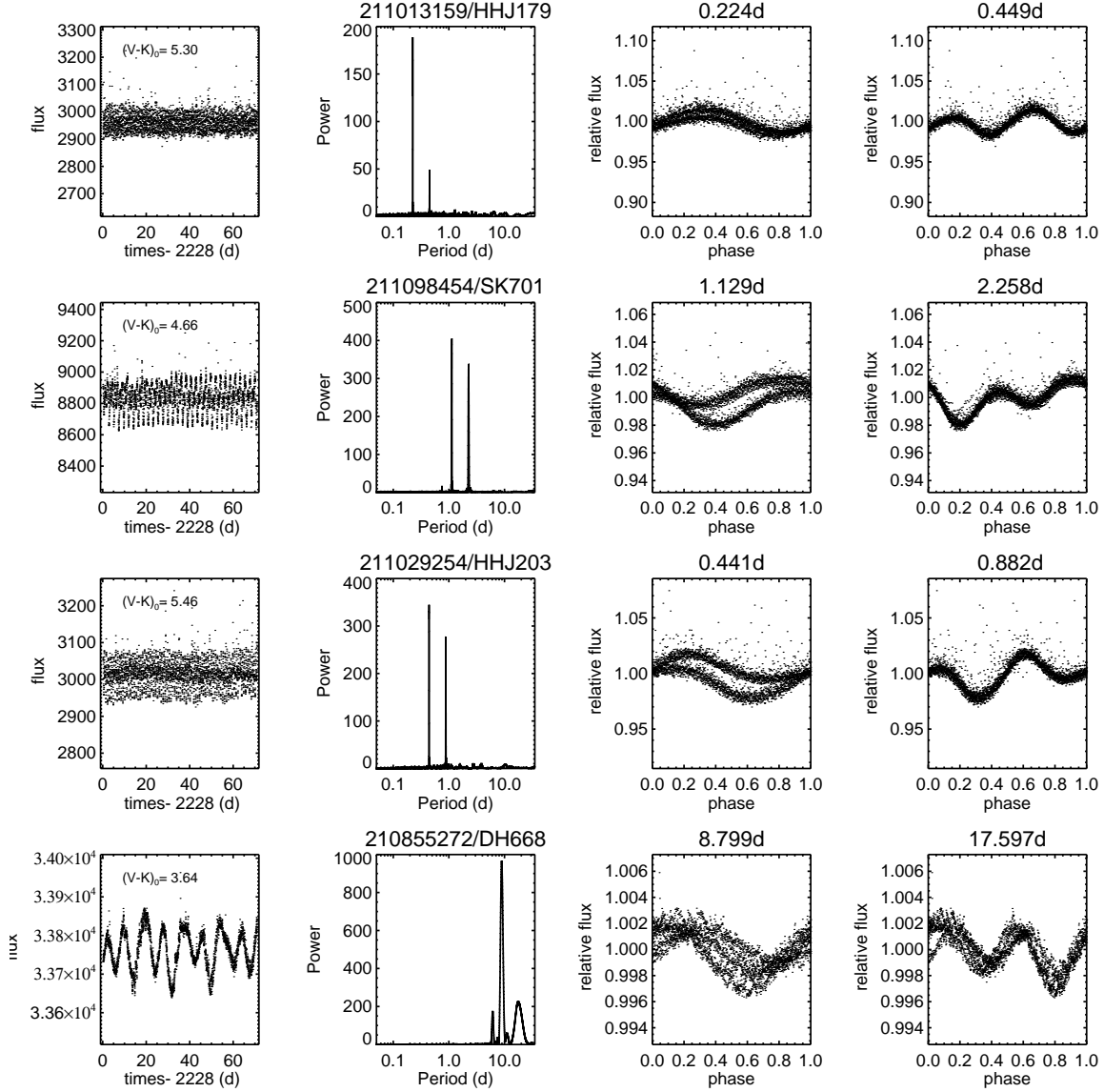


Figure 1. Four examples of the double-dipped category, where the double-dipped structure in the LC ‘fools’ the periodogram such that the maximum peak in the periodogram is half the true period. First column: full LC (with $(V - K_s)_0$ for star as indicated); second column: LS periodogram; 3rd column: phased LC with P corresponding to the maximum peak in the periodogram; 4th column: phased LC, with best period (in days) as indicated. Rows, in order: EPIC 211013159/HHJ179, 211098454/SK701, 211029254/HHJ203, and 210855272/DH668. These are representatives from a range of brightnesses and periods. In these cases, the double-dipped structure redistributes power from P into $P/2$ because the dips are of comparable depth. These LCs most likely result from stars with two spots or spot groups on well-separated longitudes. (NB: 210855272/DH668 is discussed in Paper I, because the longer period identified here makes it an outlier in the P vs. $(V - K_s)_0$ plot, but the shorter period would move it ‘into line’ with other stars of its $(V - K_s)_0$. However, we believe the longer period is correct for this star.)

power in the harmonics. (For examples of LCs where there are multiple dips but nearly all the power is in the correct P , see the single-period examples in Fig. 6 below.) For all the single-frequency, \sim sinusoidal LCs in our set, the median ratio of the power of the main peak (in the periodogram) to the second peak power is ~ 14 . For the double-dip LCs, the median of this power ratio is ~ 2 .

In some cases, inspection of the LC shows a double-dip structure over only part of the K2 campaign, or there are other slow changes over the K2 campaign such that the double-dip structure may be transient or the location of one of the minima changes slowly with respect to the maxima over the campaign. These changes are not large enough to, on their own, generate enough power in a secondary period, so no secondary period can be identified; these changes also mean that the power may not be redistributed into a subsidiary peak to the same degree as the rest of this category for a periodogram calculated over the entire K2 campaign. These so-called “moving double-dip” stars are identified

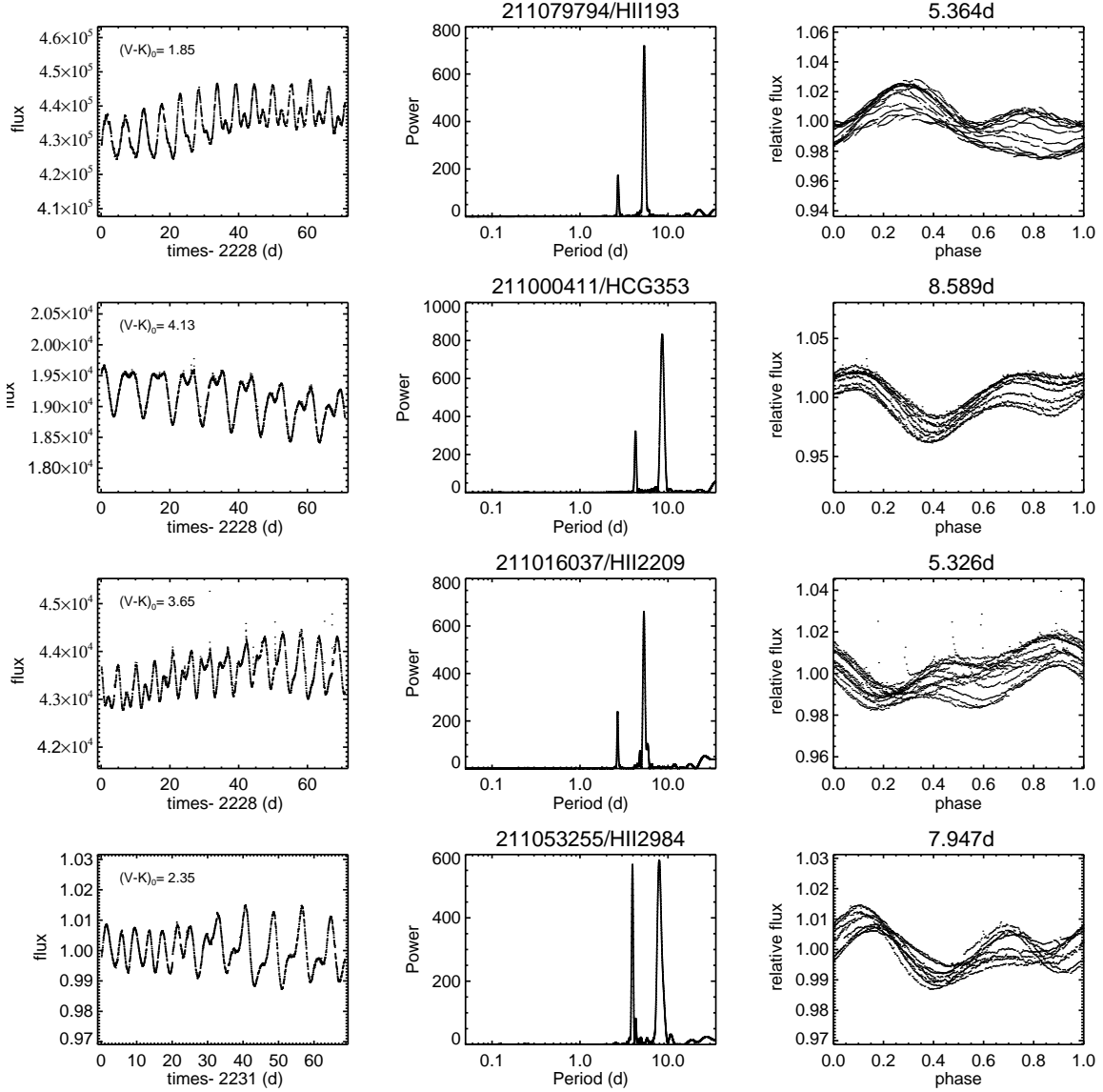


Figure 2. Four examples of the moving double-dipped category, where there is a double-dipped structure in the LC, as in prior figure, but there are visible changes in the relative locations of the structure over the campaign. First column: full LC (with $(V - K_s)_0$ for star as indicated); second column: LS periodogram; 3rd column: phased LC, with best period (in days) as indicated. Rows, in order: 211079794/HII193, 211000411/HCG353, 211016037/HII2209, and 211053255/HII2984. These LCs most likely result from stars with two spots or spot groups at different latitudes with differential rotation and/or spot evolution. Also see §3.5.

by eye and are a subcategory of the overall double-dip category; examples are given in Fig. 2. (These moving double dip stars are also ‘shape changers’; see Sec. 3.5 below.)

Most of the stars in this category have only one real period. However, some of these double-dip LCs have at least one additional periodic signal, which may or may not also have the same double-dip effect that rearranges the power distribution. (For an example where two periods are found that are both double-dip, see 211054634/HHJ291 in Fig. 4 below.)

For completeness, we add that there are a few borderline cases (such as 211048126/HII1321) where the power spectrum has some signatures of this sort of effect (harmonic at $2P$ rather than $P/2$, and/or strong harmonic at $P/2$), but the phased LC is not convincing. Those have not been included in this category.

These double-dip light curve structures are most likely to be caused by spots well-separated in longitude on the star, as in Davenport et al. (2015). There is no preferential $(V - K_s)_0$ color for these kinds of objects on the whole (see discussion in §5 below); they are found at all colors for which we have K2 spot-modulated light curves, as would be expected for spot periods. However, there are strong correlations between the stability of the pattern and $(V - K_s)_0$;

the moving double-dip are all earlier types, with $1 \lesssim (V - K_s)_0 \lesssim 4.6$ (FGK and early M). Almost all the stationary double-dip objects have $(V - K_s)_0 \gtrsim 4$; there are a few with $3 \lesssim (V - K_s)_0 \lesssim 4$.

Those that show movement of one dip/hump with respect to the other over the K2 campaign could be explained by spot/spot group formation or migration with strong latitudinal differential rotation. Those that do not show such changes, therefore, are more likely to be rotating as solid bodies, or at least have weaker latitudinal differential rotation and/or more spot stability. Although there is a huge range of P for moving and stationary double-dip objects, the moving double-dip objects are on the whole rotating slower than the stationary double-dip objects. Faster rotation should yield a more dipolar magnetic field and more stable spots/spot groups; see discussion in Paper III.

3.2. Beating LCs

About 16% of the sample (18% of the periodic sample) have obvious signatures of beating in the LC, such as changes in the envelope over the campaign; see Figure 3. Most of those have some combination of obvious beating in the LC and multiple frequencies in the periodogram (but are not the double-dip phenomenon above). For these, phasing to the maximum peak in the periodogram does not show a very well-phased LC, because of the structure provided by the subsidiary peak(s). Phasing the LC at the subsidiary peak(s) shows similar coherence (or lack thereof) for the same reason, even when the false alarm probability (FAP) is low.

We identified LCs with these kinds of properties initially by eye based on structure in the LC or in the power spectrum. We then performed an additional LS periodogram analysis with much finer frequency sampling than our initial approach, but only between $P/3$ to $3P$, for the period with the maximum power. We noticed primarily two kinds of periodogram structure. One kind has a measurably wide primary peak, and/or an asymmetric primary peak. The other kind has peaks that are very narrow, and the main power peak breaks into two (or sometimes more) resolved components. Often a secondary peak that appeared at first glance to be a harmonic is not, in fact, a true harmonic of the main peak. Sometimes the multi-peaked or asymmetric structure seen in the main peak can also be found in its harmonic (see below and Fig. 3).

We discuss the complex power spectrum peaks and those with resolved multiple frequencies in the next two subsections, respectively. We note, however, that in a few cases, the LC is seen to have a beating structure, but the components are not resolved in the power spectrum; that is, the peak is still thin, and no other significant peaks are noted. In a few cases, it seems that the *frequency* is not changing, but the *amplitude* of one or both of the signals is changing. In the remainder of the cases, it seems that the periods are so close together that the 72-day campaign does not provide enough cycles to distinguish the periods.

When the LC looks ‘beating’, and/or there are complex power spectrum peaks, there are 3 possible interpretations: (a) spots or spot groups evolving; (b) latitudinal differential rotation from spots/spot groups at more than one latitude during the K2 campaign; (c) spot modulated periods from two (or even three) unresolved stars in the K2 aperture. The majority of the stars identified as beaters are the earlier types, $(V - K_s)_0 \lesssim 4$, which is where strong latitudinal differential rotation is expected.

3.3. Complex, Structured Peaks and Unresolved Multi-Period Peaks

To find objects where the peak(s) in the periodogram are distinctly broad and/or structured, we took multiple approaches; examples are shown in Fig. 3. About 11% of the sample (12% of the periodic sample) falls into this category of complex, structured peaks and unresolved multi-period.

First, for all of these objects, we computed a power spectrum with finer frequency resolution, as discussed above. If the maximum peak is clearly asymmetric (such as seen in the first and last rows of Fig. 3), then we added the star to this category on the basis of having “complex, structured peaks.” If the higher frequency resolution power spectrum incompletely resolves the peak into pieces (as seen in the second row of Fig. 3, where the wings of the peaks run into each other at power levels > 0), then we added the star into this category on the basis of having a “complex peak.”

Finally, to assess whether or not the peak is broader than expected for its period, we took the full-width-at-half-max (FWHM) of the actual peak (*not* the FWHM of, say, a Gaussian fit to the peak, but the true FWHM of the peak), and plotted that as a function of period. For most of the sample, this relationship falls on a line when plotted in log-log space³. We fit the line, subtracted it from the distribution, and looked for things that deviated significantly from 0. This is not a good approach for identifying, say, objects like the first and last rows in Fig. 3, because the additional structures seen near the base of the peaks do not affect the half maximum. However, the object in the third

³ The expected peak width (where f is frequency) is $df \sim 1/T$ (where T is the total length of the campaign), which is independent of period, and consequently $dP = df \times P^2$.

row of Fig. 3 has a peak much broader than expected for stars with single periods near 10.3d. This is the final type of object added to this “complex peak” category – those with peaks wider than expected for that period. In these cases, the period is changing over the campaign, and/or the multiple periods are so close together that the power spectrum cannot resolve them.

These kinds of power spectra are very suggestive of latitudinal differential rotation and/or spot evolution. Periods that are very close together and/or changing over the K2 campaign, could easily be explained if we are seeing spots at different latitudes in a differentially rotating star, either spots that persist over the K2 campaign or spots that appear, disappear, or otherwise change over the K2 campaign. The majority of the stars identified as having complex peaks are the earlier types, $(V - K_s)_0 \lesssim 4$, which is where strong latitudinal differential rotation is expected.

3.4. Resolved Multi-Period

In some cases, there are well-resolved, very narrow peaks in the power spectrum and both periods are real; see Figure 4. The periods need not be very close together and they are not harmonics, though sometimes the harmonics appear (first row of Fig. 4). About 20% of the sample (22% of the periodic sample) fall into this category of resolved periods.

We wished to differentiate situations as in the second row of Fig. 4, where the peaks are very close together, and situations as in the last row of Fig. 4, where the peaks are substantially farther away from each other. For every situation in which we had at least two viable periods for a star, we took the closest two periods out of those detected, subtracted the smaller from the larger, and divided by the primary peak. The primary peak is the strongest in the power spectrum, and what we take to be the rotation period of the primary star in the system, but may or may not be one of the two closest peaks. If that metric, $\Delta P/P_1$, is less than 0.45, then we take it to be resolved close peaks; if that metric is greater than 0.45, then we take it to be resolved distant peaks. This dividing line of $\Delta P/P_1 = 0.45$ was determined by inspection of the light curve and periodogram properties, as well as the morphology of the $\Delta P/P_1$ distribution; see much more discussion in Sec. 6 below.

Of the $\sim 20\%$ of the sample that falls in this broader category of resolved peaks, 73% are tagged close, and 30% are tagged distant. Note that some objects have both close and distant peaks. Both resolved close and resolved distant periods are found at all $(V - K_s)_0$; the distant periods are equally likely at all $(V - K_s)_0$, but the close periods are slightly more frequent (as a fraction of the sample) for $(V - K_s)_0 \lesssim 3.7$.

Particularly for the stars with $(V - K_s)_0 \lesssim 3.7$ and having resolved close periods, we suspect that these are another manifestation of latitudinal differential rotation and/or spot evolution. For the resolved distant periods, we suspect that they are binaries, where the two different periods are the different rotation rates of the components of the binary. For $\sim 60\%$ of the stars in this category, there is at least some evidence that it is a binary or there is more than one star in the K2 aperture; for the rest, there is no information suggesting binarity, but in many cases, this may reflect simply a lack of data.

3.5. Shape Changers

There is a category of LC where the power spectrum suggests that there is just one period derived from the data, but there are visible, substantial changes in the shape of the light curve over the campaign. These so-called shape changers are $\sim 14\%$ of the sample ($\sim 15\%$ of the periodic sample).

Examples are seen in Figure 5 (also see Fig. 2 for the moving double-dips, which are also shape changers). Sometimes the overall envelope of the LC changes, manifesting as changes in shape of the phased LC. In other cases, one can see additional structure appear in the LC and grow in strength, or even move with respect to the other structures in the LC over the course of the campaign.

Spot evolution seems like a likely physical interpretation; one can imagine a new spot or spot group appearing or disappearing over the campaign to create these LCs. For those where structure in the LC moves with respect to other structures in the LC, spot evolution combined with latitudinal differential rotation could explain the observations. We note, though, that there are other LC categories where we find two or more periods that we attribute to latitudinal differential rotation and/or spot evolution. In the case of shape changers, the changes are evidently happening more slowly, such that there are not enough rotation periods (and/or stability in the periods), and so an additional period cannot be resolved. If we were able to obtain light curves over more than 72 days, perhaps a second (or third) period could be derived, in which case some of these stars could end up in the ‘complex peaks’ and/or ‘beater’ categories above.

The shape changers have $1 \lesssim (V - K_s)_0 \lesssim 5$. While the $(V - K_s)_0$ range for shape changers overlaps that for beaters and complex peaks, the shape changers extend to redder $(V - K_s)_0$; see additional discussion below and in Paper III.

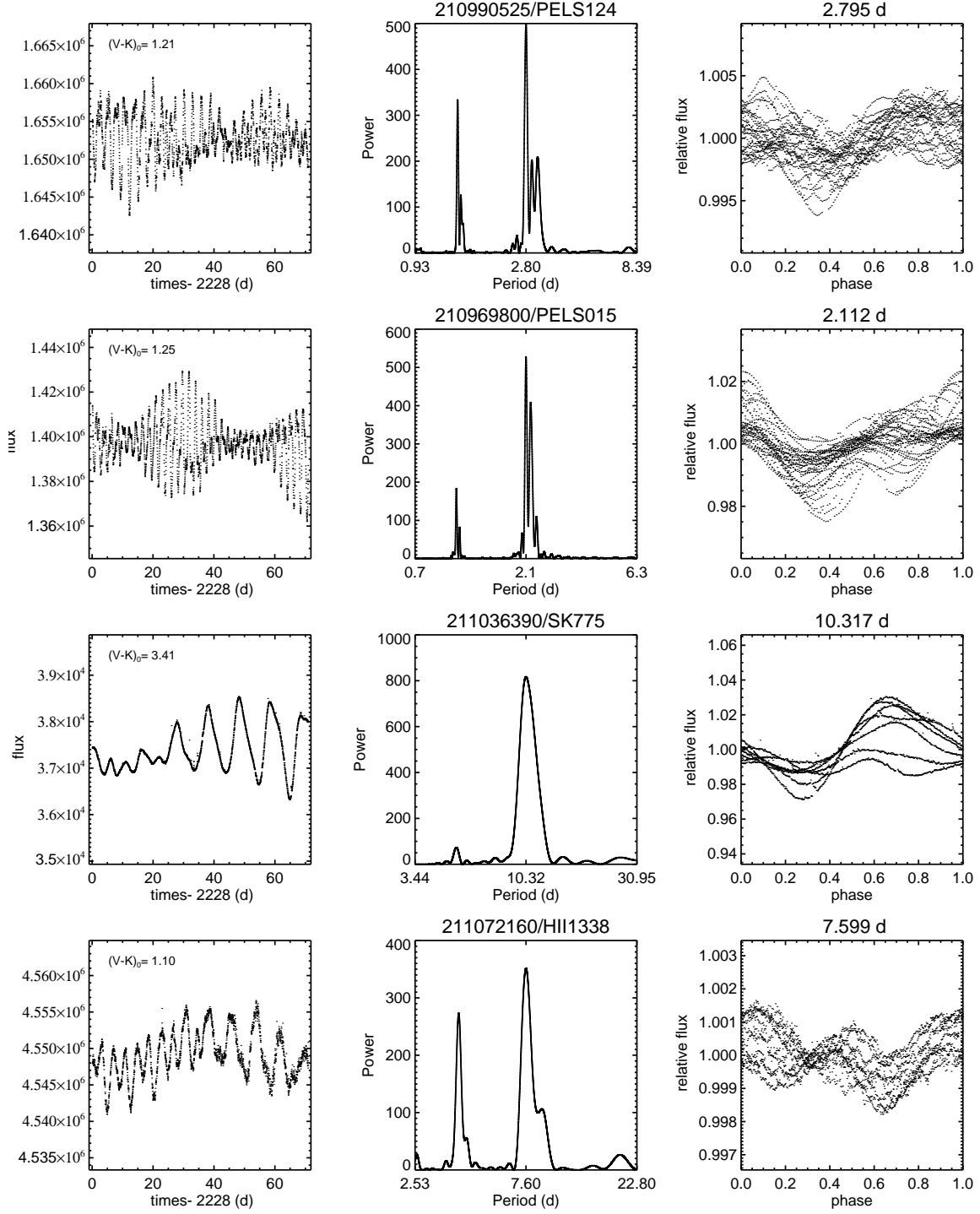


Figure 3. Four examples of the beater and complex peak categories. Beating is seen in the LC, and for these examples, the peak in the periodogram is complex, broad, and/or structured. Left column: full LC (with $(V - K_s)_0$ for star as indicated); middle column: periodogram; right column: phased LC for maximum peak. Rows, in order (with the periods corresponding to significant peaks in parentheses): 210990525/PELS124 (2.795, 1.421, 3.330), 210969800/PELS015 (2.112, 2.212), 211036390/SK775 (10.317), and 211072160/HII1338 (7.599, 8.899). Note that the power spectrum shows peaks of measurable width and/or multiple peaks. Sometimes the multi-peaked structure can be found both in the main peak and its harmonic. These LCs are likely a result of latitudinal differential rotation and/or spot evolution.

About 60% of the shape changers are also in another category described above.

3.6. Orbiting Clouds?

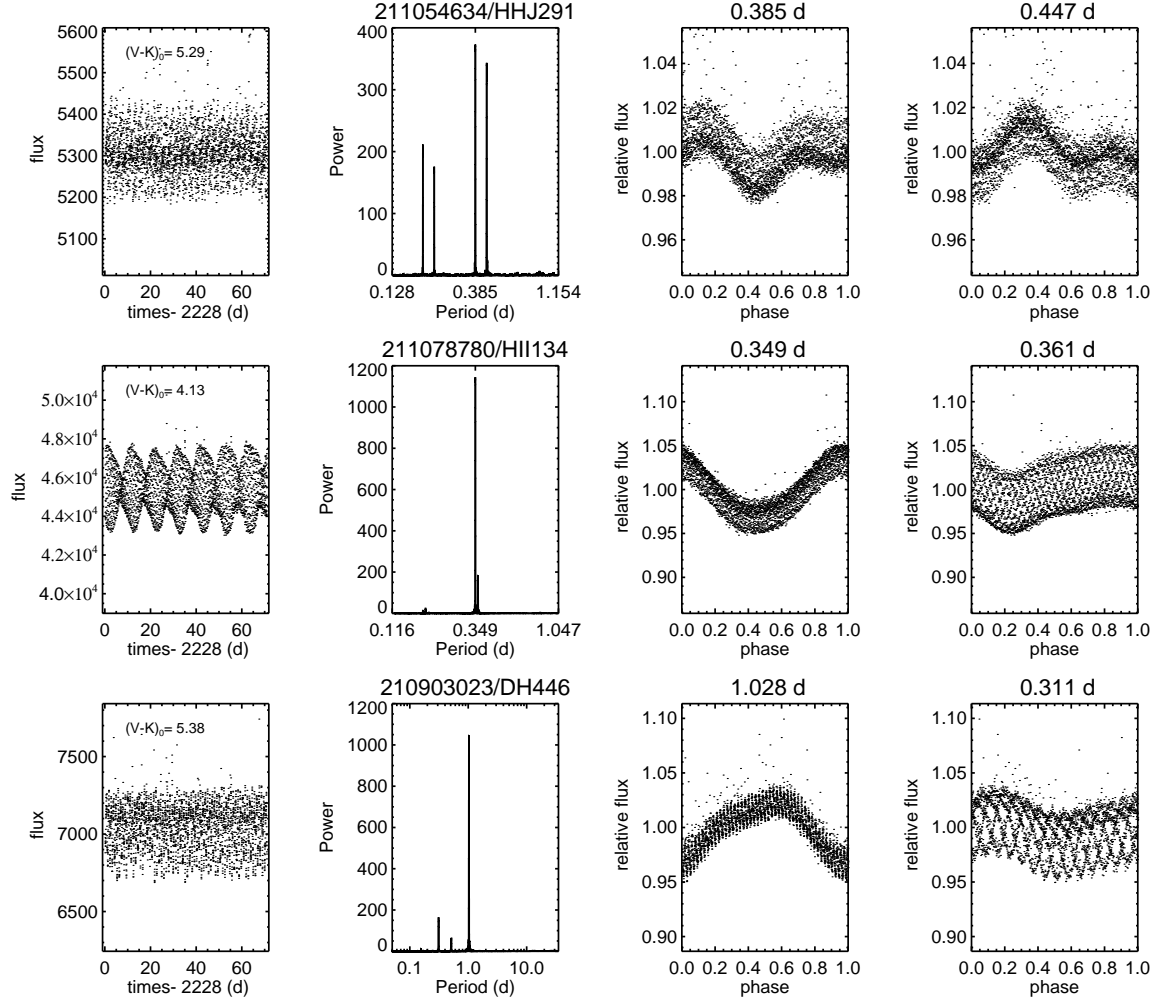


Figure 4. Three examples of the resolved peak categories, LCs where there are 2 distinct, well-resolved frequencies. First column: full LC (with $(V - K_s)_0$ for star as indicated); 2nd column: periodogram; 3rd column: phased LC for primary peak; last column: phased LC for secondary peak. Rows, in order (with the periods corresponding to significant peaks in parentheses): 211054634/HHJ291 (0.385, 0.447; $\Delta P/P_1=0.162$), 211078780/HII134 (0.349, 0.361; $\Delta P/P_1=0.035$), 210903023/DH446 (1.028, 0.312; $\Delta P/P_1=0.698$). Note that the power spectrum shows multiple, resolved peaks. Following the $\Delta P/P_1$ metric divisions, the first and second have resolved close periods (the two peaks are very close together in the periodogram), and the third has resolved distant peaks. All three of these have companions that can be seen in POSS or Robo-AO data, so these LCs are likely to result from binaries, with one period per star.

In six cases, the period we identify in the power spectrum yields a phased light curve of unusual shape; see Fig. 6. The phased light curves show shallow, angular dips (highlighted with arrows in Fig. 6) which cover a relatively small portion of the total phase. The pattern is stable (or nearly stable) over the 72 day K2 campaign. In several cases, the light curves also show broad dips, which presumably are due to cool spots on the stellar surface. Half of these stars have an additional secondary period. Four are high-quality members, one is a lower quality member (211013604/HCG332) and one is a probable non-member (211144341/BPL300). About 0.6% of the sample (0.7% of the periodic sample) have these structures.

The narrowness of the highlighted dips seem difficult to explain with cool spots, yet they are too broad to be due to transits of secondary stars or giant planets. The basic information for these stars is all in Table 1; all of them are fairly late M dwarfs, and all have periods < 0.7 d, which means they have fairly normal periods for Pleiades stars of this mass.

We have identified two possible physical explanations for the shallow dips in these light curves. First, they could be due to eclipses of warm, dense circumstellar clouds formed near the top of large coronal loops and temporarily held near the Keplerian co-rotation radius by centrifugal force (Collier Cameron 1988; Collier Cameron & Robinson 1989). Such clouds have been identified in synoptic spectra of several rapidly rotating, young dwarfs (*e.g.*, AB Dor), though

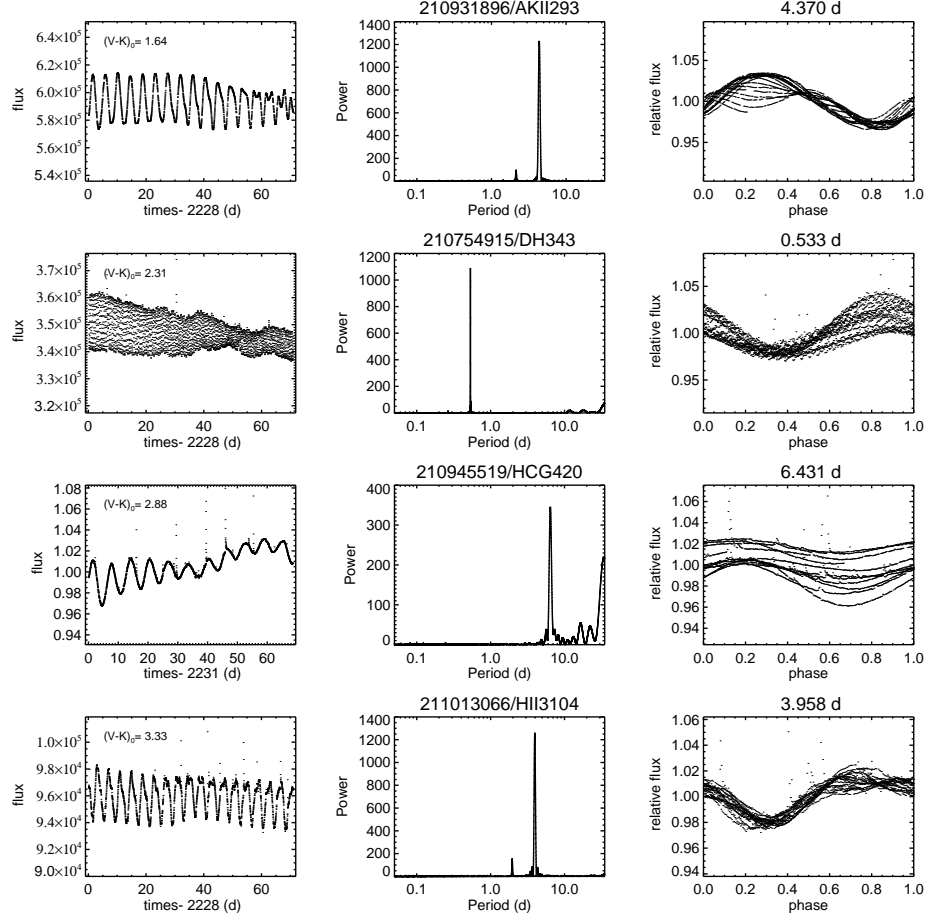


Figure 5. Four examples of the shape changer category, LCs where there are changes in the shape of the LC over the K2 campaign. Left column: full LC (with $(V - K_s)_0$ for star as indicated); middle column: periodogram; right column: phased LC for maximum peak. Rows, in order: 210931896/AKII293, 210754915/DH343, 210945519/HCG420, 211013066/HII3104. Note that the power spectrum shows a single peak, but the shape changes over the campaign. Assuming that these shapes are a result of spot evolution, sometimes it looks like a new spot or spot group is appearing or disappearing over the campaign. It is likely that if we had a longer campaign, then these objects would be instead in one of the complex peak/resolved peak categories, but 72 days is not long enough to distinguish the frequencies.

not previously in time series photometry. For at least four of the six stars, the cloud associated with the narrow dip would be located near the corotation radius since the periods for the narrow and broad dips are apparently the same, or nearly the same. In two cases, the narrow dip appears to move slightly in phase relative to the broad dip or to another narrow dip; differential rotation is very unlikely in these stars, given their spectral type and rotation rate.

The other possible physical mechanism for the narrow dips is that they could be due to comets or some other form of “debris” orbiting these stars, perhaps similar in some respects to stars from the main Kepler field recently found to show transient, shallow flux dips (Boyajian et al. 2016; Vanderburg et al. 2015). In this case, the dips would be associated with transits of these dusty structures in front of the star. It is not obvious why material would be located near the Keplerian co-rotation radius so frequently in this model.

If these objects have orbiting particulate debris, one might expect an IR excess from the debris. However, none of these objects have truly compelling evidence for an infrared (IR) excess; the longest wavelength detection for any of them is WISE-3, 12 μm , which is detected in four of the six stars. The most likely excess is found in 211013066/HCG332, which has $[3.4] - [12] = 0.53$ mag and the metric often used to assess significance of excess, $\chi = ([3.4] - [12]) / \sqrt{\sigma_{[3.4]}^2 + \sigma_{[12]}^2}$, is 5, so not very obvious. The other stars with 12 μm detections have similar sized $[3.4] - [12]$ but less significant χ . Moreover, only a small fraction of dust could account for these dips; see, *e.g.*, Gillen et al. (2014), Terquem et al. (2015), and Gillen et al. (2016). Further investigation is warranted, such as monitoring in different wavelengths, and a more careful assessment of any small IR excesses.

HCG332 is one of two stars originally made famous in Oppenheimer et al. (1997). This work reported results of a

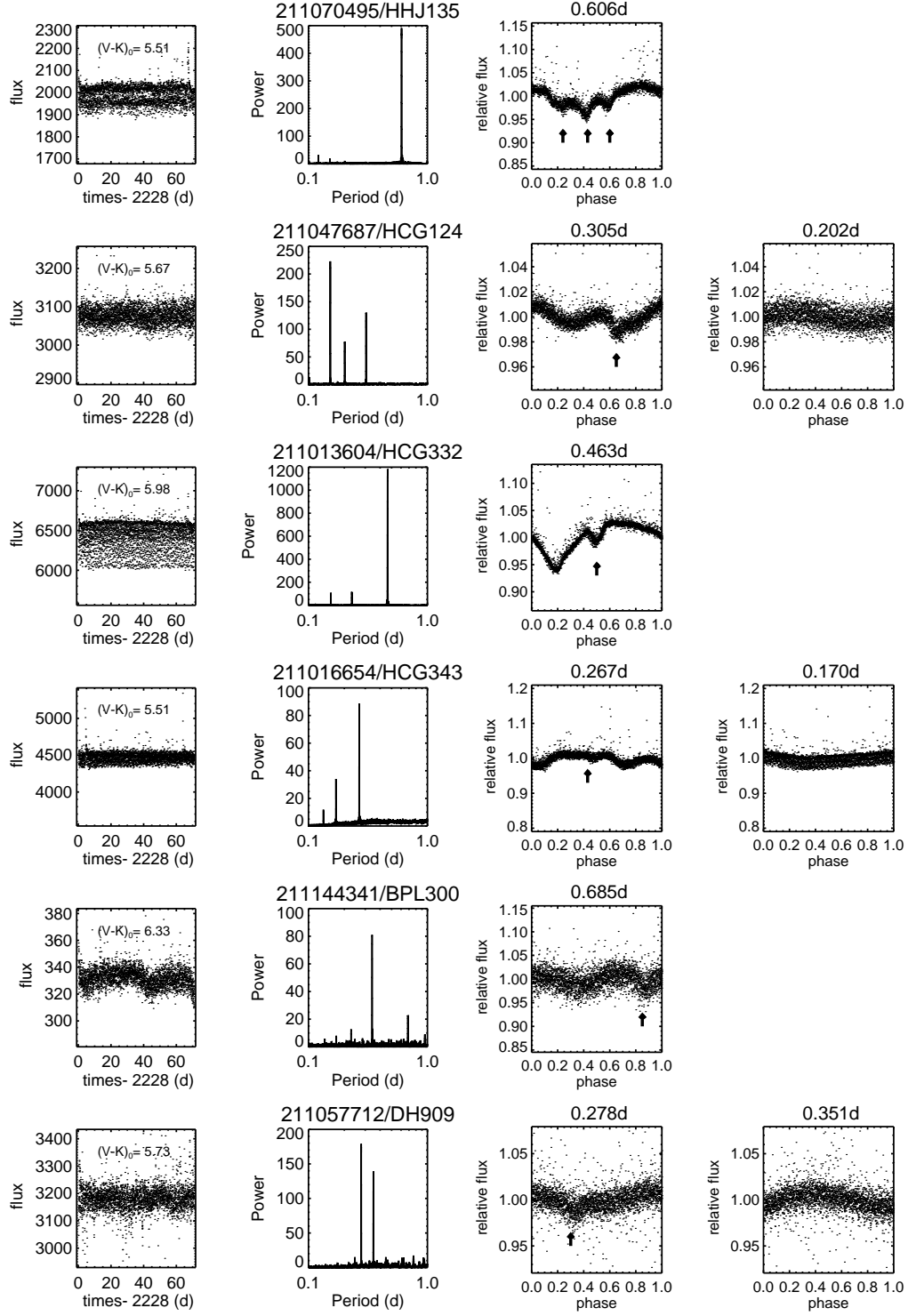


Figure 6. All six stars identified as having repeated, angular, brief dips in their light curves. First column: full LC (with $(V - K_s)_0$ for star as indicated); second column: periodogram; third column: phased LC for maximum peak; fourth column: phased LC for secondary peak, if present. Rows, in order: 211070495/HHJ135, 211047687/HCG124, 211013604/HCG332, 211016654/HCG343, 211144341/BPL300, 211057712/DH909. Arrows in the first phased LC indicate the shallow, angular dips discussed in Sec. 3.6. These LC structures may be due to orbiting clouds or debris.

search for lithium in very low mass members of the Pleiades; they were attempting to identify stars at the lithium depletion boundary marking the point cooler than which Pleiades age stars have not reached core temperatures hot enough to burn lithium. Oppenheimer et al. found no stars fitting the criteria to be at the lithium depletion boundary,

Table 3. Pulsators

EPIC	Other name	SpTy	Notes
211018096	HD23791=HII1993	A8	Identified <i>a priori</i> by us as a pulsator, $P \lesssim 0.1$ d; obvious δ Scuti
211044267	HII1425	A3V	Identified <i>a priori</i> by us as a pulsator, $P \lesssim 0.1$ d; obvious δ Scuti; literature-identified δ Scuti (Breger 1972, Fox Machado 2006); in Fig. 7
211057064	HD23863=HII2195	A7V	Identified <i>a priori</i> by us as a pulsator, $P \lesssim 0.1$ d; obvious δ Scuti
211066615	HII652	A3V	Identified <i>a priori</i> by us as a pulsator, $P \lesssim 0.1$ d; obvious δ Scuti
211080847	HII531	A9m ^a	Identified <i>a priori</i> by us as a pulsator, $P \lesssim 0.1$ d; obvious δ Scuti; in Fig. 7
211062007	HII2866	A2V	Identified <i>a priori</i> by us as a pulsator, $P \sim 0.3$ d; likely δ Scuti; in Fig. 7
211086138	HD23763=HII1876	A1V	Identified <i>a priori</i> by us as a pulsator, $P \sim 0.3$ d; likely δ Scuti; in Fig. 7
211093705	HII697	A9	Identified <i>a priori</i> by us as a pulsator, $P \sim 0.3$ d; likely δ Scuti; literature-identified δ Scuti (Breger 1972)
211115721	HII1266	A9V	Literature-identified δ Scuti (Fox Machado et al. 2006), not identified by us, for which we have just one (long) period
211072836	HII1362	A7	Literature-identified δ Scuti (Fox Machado et al. 2006), not identified by us because star too bright
211088007	HII158	A7V	Literature-identified δ Scuti (Fox Machado et al. 2006), not identified by us because star too bright (though knowing that it is a pulsator, one can identify the likely relevant periodogram peaks)
211101694	HII1384	A4V	Literature-identified δ Scuti (Fox Machado et al. 2006), not identified by us because star too bright (though knowing that it is a pulsator, one can identify the likely relevant periodogram peaks)

^a All of the spectral types here come from Mendoza (1956), except for this one, HII531, which Mendoza (1956) lists as “Am?,” but Gray et al. (2001) give a more definitive A9m.

but they did identify two purported, somewhat higher mass Pleiades M dwarfs that had strong lithium features when no lithium should be present. (The other star is HCG509, discussed in Paper I’s Appendix.) Both stars are located >1 mag above the Pleiades single-star main sequence, which they interpreted to mean they are very young pre-main-sequence stars and not Pleiades members. We will report elsewhere on the implications for models of these two stars based on their K2 lightcurves and additional spectroscopy (Barrado et al. in prep).

3.7. Pulsators and Rotation

Throughout most of the mass range of interest to this paper, rotational modulation due to star spots provides the only plausible physical mechanism to explain the periodic LCs we see. However, at the high mass end of our sample ($(V - K_s)_0 \lesssim 1.3$, $M \gtrsim 1.2 M_\odot$), pulsation may provide an alternative explanation.

In eight cases ($\sim 1\%$ of the sample), the power spectrum reveals a ‘forest’ of significant (FAP=0) peaks in the periodogram, all at very short periods; see Figure 7 for examples and Table 3 for a list of these stars. They are also all very small amplitude LCs (median 0.0027 mag). In most cases, these must be pulsators; if interpreted as rotation periods, the period would exceed the break-up limit. They are all earlier types – their $(V - K_s)_0$ ranges from 0.24 to 0.85 (mid-A to early F). Five of the eight stars we have identified in this category have periods $\lesssim 0.1$ d; the other three are all ~ 0.3 d and include both the bluest and reddest $(V - K_s)_0$ of this category (spectral types A1, A2, and A9; see Table 3).

Delta Scuti stars have spectral types A or F, and periods typically $\lesssim 0.3$ d (*e.g.*, Breger 1979). They are lower mass Cepheid analogues. Several of the Pleiades with K2 LCs have been identified in the literature (Breger 1972, Fox Machado et al. 2006) as being δ Scuti pulsators, but most of them are too bright for us to reliably identify a period at all with the light curve versions we have, much less a pulsator-type power spectrum. Two of them are ones we identified as pulsators, and the rest are very bright; see Table 3. For two of these bright stars, knowing that they are thought to be pulsators, one can find the likely relevant peaks in the power spectrum in amongst the noise, but the light curve is significantly compromised and we did not identify these periods *a priori*.

We suspect that the remaining stars we identified as likely pulsators are also δ Scutis, particularly the three with the shortest periods. The other three near ~ 0.3 d are at the outer edge of the accepted range for δ Scuti periods, as well as the outer edge of the expected spectral type range. However, given the spectral types for the stars already in the literature as δ Scutis (see Table 3), perhaps the spectral type range for these pulsators is not so rigidly defined. We thus identify all six of our *a priori* identified pulsators as δ Scutis. No modern $v \sin i$ values are available for these stars in the literature.

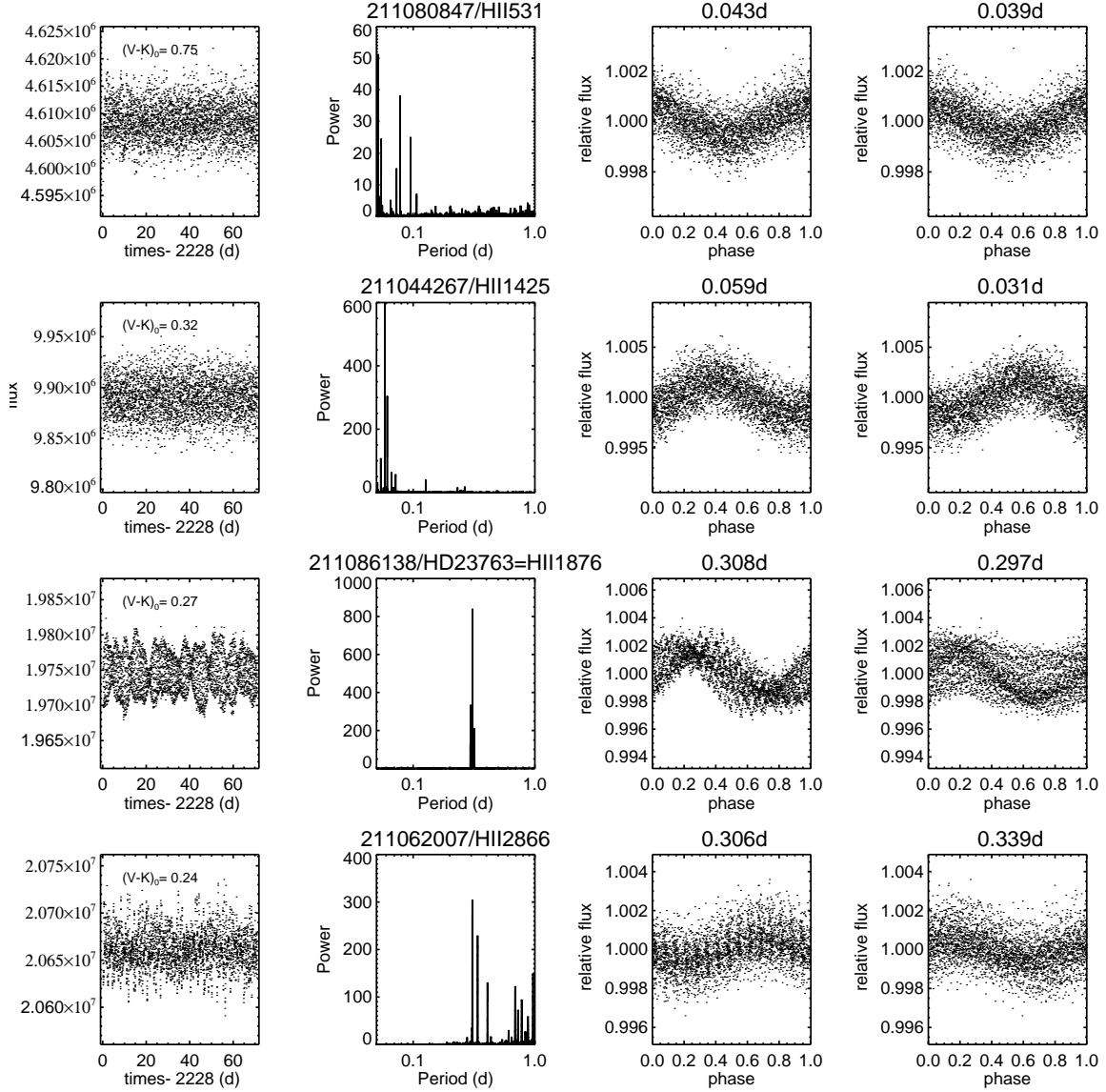


Figure 7. Four examples of the pulsator category, stars that are likely δ Scuti pulsators. First column: full LC (with $(V-K_s)_0$ for star as indicated); second column: LS periodogram; 3rd column: phased LC at the P with the highest peak in the periodogram; 4th column: phased LC at the P with the second highest peak in the periodogram. Rows, in order: EPIC 211080847/HII531, 211044267/HII1425, 211086138/HD23763=HII1876, 211062007/HII2866.

The δ Scutis are relatively easily identified due to their very short periods that essentially cannot be ascribed to rotation because the inferred rotational velocities would exceed breakup. However, another type of pulsating variable is γ Dor type pulsators (*e.g.*, Krisciunas 1994; Kaye et al. 1999), which may have the same underlying physics as δ Scutis (*e.g.*, Xiong et al. 2016). Gamma Dors are also A or F stars, but are pulsating with on average longer periods, ~ 0.4 to 3 days (*e.g.*, Balona et al. 1994, Kaye et al. 1999). These are harder to distinguish from rotation periods, because their periods overlap with expected spot-modulated rotation periods for their masses.

It has been shown that for stars identified as γ Dors in the main Kepler field, the measured periods correlate well with $v \sin i$ values for those stars (Balona et al. 2011) and similarly for γ Dors not necessarily in the Kepler field (Kahraman Aliçavuş et al. 2016). This suggests that it might be difficult to discriminate between pulsation and rotation as the drivers of the observed variability for at least some of our F stars. In fact, Balona et al. (2011) acknowledge that many of the stars they identify as γ Dor variables in the main Kepler field may instead owe their variability to rotation and star spots. Bradley et al. (2015), despite selecting targets specifically to look for γ Dor and δ Sct stars in the instability strip in the Kepler field, find that 74% of their sample are better interpreted as spot modulation.

Our close resolved and/or complex peak categories contain many power spectra that resemble those of γ Dors

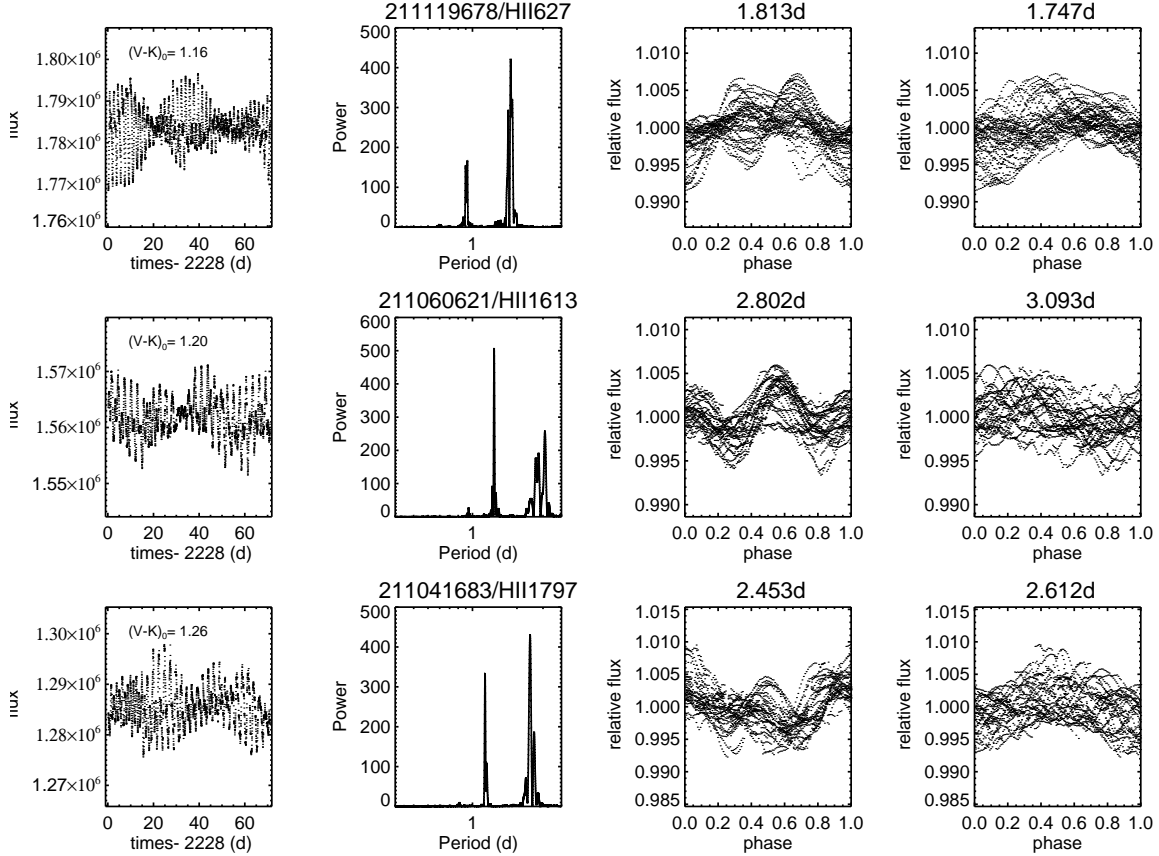


Figure 8. Examples of objects that may be γ Dors. First column: full LC (with $(V - K_s)_0$ for star as indicated); 2nd column: periodogram; 3rd column: phased LC for primary peak; 4th column: phased LC for secondary peak. Rows, in order: 21119678/HII627, 211060621/HII1613, 211041683/HII1797. The measured $v \sin i$ from the literature is ~ 33 , 20, 20 km s^{-1} , respectively, which is consistent with these being rotation rates. 210990525/PELS124 from Fig. 3 may also be in this category. (Its $v \sin i \sim 20 \text{ km s}^{-1}$ as well.)

from the main Kepler field in Balona et al. (2011), but ours extend over a much wider range of color than for just near the instability strip, down to $(V - K_s)_0 \sim 4$ for the complex peaks alone. There is no clear separation of the LC characteristics of these stars from slightly more massive or less massive stars, instead there is simply a smooth transition. There exist stars with this LC/periodogram morphology both redward and blueward of the boundaries that are expected to define the γ Dor class. Figure 8 includes the LCs and periodograms for some of the stars with γ Dor-like variability. There is a measured $v \sin i$ for each of those stars; for the measured P , the measured $v \sin i$ should be $\sim 20\text{--}30 \text{ km s}^{-1}$, which they are. For this paper, we choose to adopt the dominant LS period as the star’s rotation period for all of these stars. Given the good correlation between $v \sin i$ and period found by Balona et al. (2011) and Kahraman Aliçavuş et al. (2016), this period is unlikely to be very far from the true rotation period even if pulsation is the actual cause. Based on the wide spectral type range over which we see this type of variability and the smooth change in LC morphology as one traverses the G to F star spectral range, we believe it is likely that rotation is the correct physical mechanism to explain these kinds of LCs and periodograms, particularly for the ones with $(V - K_s)_0 > 1.1$.

4. SINGLE-PERIOD AND MULTI-PERIOD DISTRIBUTIONS

The broadest two categories of LC properties are simply single-period and multi-period stars. This section looks at where the single-period and multi-period stars fall in a variety of parameter spaces.

4.1. Period Distribution

Paper I discussed the overall period distribution. Because the sample of stars with one P dominates, the addition of all the secondary, tertiary, and quaternary periods does not change the distribution very much. Figure 9 breaks out the primary, secondary, tertiary, and quaternary periods found here separately. Even though there are far fewer

tertiary and quaternary periods (10 with tertiary periods and 5 with quaternary periods), the distributions of all four periods are still strongly peaked at $<1d$.

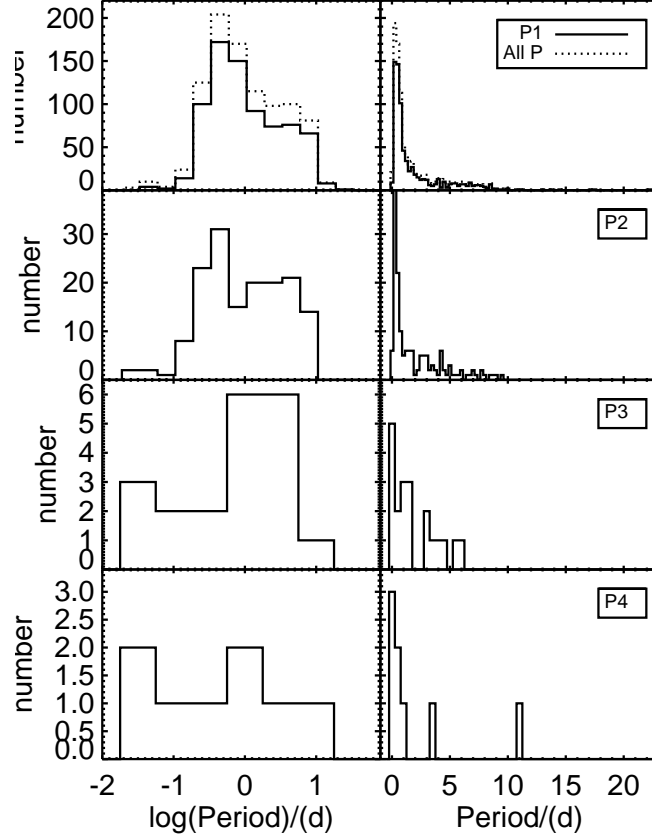


Figure 9. Histograms of the periods found by our analysis, in days. The left column contains histograms of the $\log(P)$ and the right column contains histograms of linear P . In the first row, the solid line is the primary period (that which we take to be the rotation period of the star), and dotted line is (for reference) a histogram of *all* the periods found here, including the secondary, tertiary, and quaternary periods. The second, third, and fourth rows are the secondary, tertiary, and quaternary periods plotted separately; there are many fewer tertiary and quaternary periods. The period distribution of all four periods is still strongly peaked at $<1d$.

If all of the additional periods we determined are periods of secondary stars in the unresolved binary, then the ‘true’ distribution of Pleiades rotation rates is the amalgamation of all the periods we determined, seen as the dotted line in Fig. 9. However, it is unlikely that *all* of the additional periods are binaries; it is very likely that some are pulsation and many are differential rotation and/or spot evolution.

4.2. $(V - K_s)_0$ Colors

Figure 10 shows the distribution of $(V - K_s)_0$ values for the single-period and multi-period categories. The earlier types (bluer colors, G & K dwarfs) are preferentially multi-periodic, and the later types (redder colors, M dwarfs) are preferentially single-period, though about 30% of the earlier types have only one period that we can detect, and about 20% of the later types have multiple periods. Many of the earlier types categorized as having only one period also have broad periodogram peaks, suggesting that they really are multi-periodic; we just cannot ascertain exactly what that additional frequency is.

4.3. Amplitude Distribution

The LCs with multiple periods are on average slightly lower amplitude than those with single periods; see Figure 11 (and see Paper I, section 3.3 for the definition of amplitude employed here). For the single period sample, the mean amplitude (10-90% of the points fall within this range, in magnitudes) is 0.0399 ± 0.0321 mag. For the multi-period

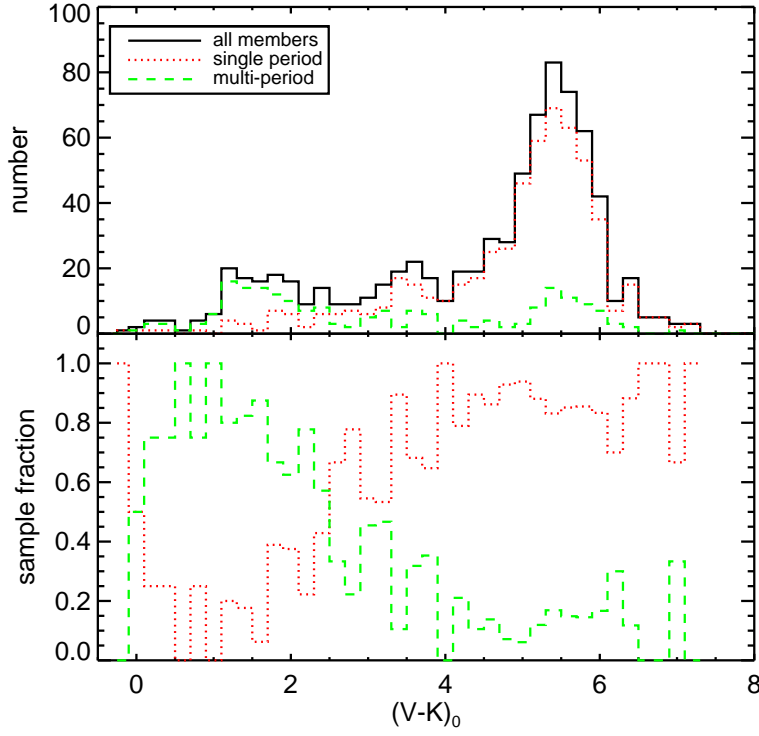


Figure 10. Distribution of $(V - K_s)_0$ for the ensemble, with the single (red dotted) and multiple (green dashed) populations called out. The top panel is absolute numbers, and the bottom is the sample fraction. The earlier types (bluer colors) are preferentially multi-periodic, and the later types (redder colors) are preferentially single-period, though about 30% of the earlier types have only one period that we can detect, and about 20% of the later types have multiple periods. Note that the place where the single and multi-period distributions swap dominance in the lower panel is at about $(V - K_s)_0 \sim 2.6$, the location of the ‘kink’ discussed in Paper III.

sample, the mean is 0.0250 ± 0.0183 mag. Considering just $(V - K_s)_0 > 1.1$ to remove the possible and likely pulsators (also see discussion in Paper III), the single period sample is nearly unchanged at 0.0403 ± 0.0321 mag and the multi-period sample is 0.0274 ± 0.0176 mag; the multi-period amplitudes are still on average smaller than the single-period amplitudes. Removing the distant resolved peaks as likely binaries (where the amplitude may be diluted by the companion) makes little difference in the means because there are relatively few of them. There are essentially no multiperiodic stars with amplitudes above 0.08 mag, but the stars with single frequencies include many up to 0.13 mag. This is likely why little if any of this diversity of multi-period stars in the Pleiades has been discovered prior to these K2 data. (We note, however, that stars with beating light curves have been observed in non-Pleiades CoRoT and Kepler data, such as Nagel, Czesla, & Schmitt 2016.)

The bias towards single periods at later types is probably partially a selection effect (lower signal-to-noise available in the fainter later types), but may also be due to different dynamo regimes or different spot latitude distributions. If the multi-periodic stars originate from spots at different latitudes (*e.g.*, differential rotation), then the later types, which are largely rapidly rotating, are either rotating as solid bodies or primarily have high latitude spots. We discuss this more below and in Paper III.

4.4. P vs. $(V - K_s)_0$

Fig. 12 shows the locations of the single and multi-period stars in the P vs. $(V - K_s)_0$ diagram and the color-magnitude diagram (CMD) for reference. As we suspected from Fig. 10, it is primarily the earlier types that have multiple periods, and the later types that have single periods. Most of the stars in the slowly rotating sequence with $1.1 \lesssim (V - K_s)_0 \lesssim 3.7$ have multiple periods. Most of the rest of the P vs. $(V - K_s)_0$ diagram, particularly the M stars in the fast sequence (with $(V - K_s)_0 \gtrsim 5.0$), is composed of single-period stars. Interestingly, the M stars that are multi-period in the fast sequence tend to also be above the main sequence, *e.g.*, photometric binaries. For stars redder than $(V - K_s)_0 \sim 4$, nearly all the multi-period LCs are also photometric binaries. Presumably, then, in those cases,

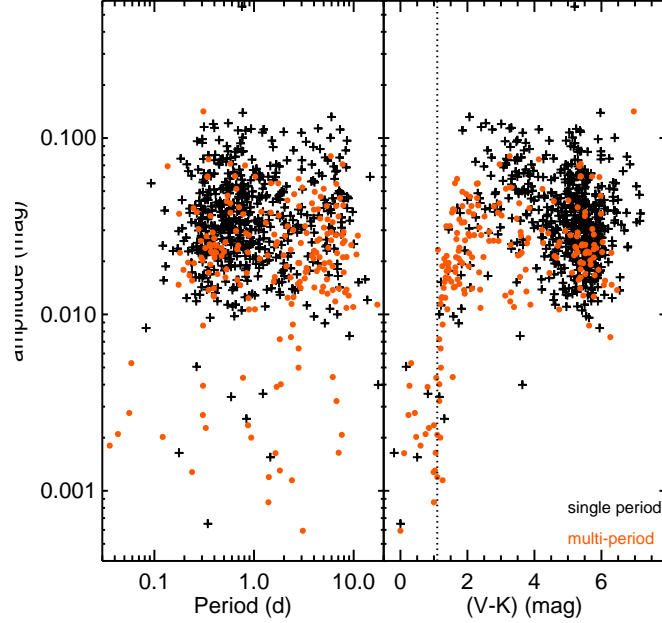


Figure 11. The amplitude (from the 10th to the 90th percentile), in magnitudes, of the periodic light curves, against P and $(V - K_s)_0$. The stars with single periods are black crosses and those with multiple periods are orange dots. The vertical dotted line is at $(V - K_s)_0 = 1.1$ (see Paper III, where there is a linear version of this plot). Stars bluer than about $(V - K_s)_0 \sim 1.1$ have clearly lower amplitudes.

the two periods we derive from the LC come from two different stars. Since most of the rest of the stars in the fast sequence seem to have single periods, and the two components of the photometric binary each have single periods, we suggest that most of the M stars have single periods, and may therefore be rotating as solid bodies, or the timescale of any shift in latitude is much longer than the K2 campaign.

5. DISTRIBUTIONS OF CATEGORIES

While the prior section investigated where single- and multi-period stars fall, we have many more than just two categories of LCs and periodogram structures; this section uses the full range of categories to explore the possible physical interpretations of the LC and periodogram shapes.

5.1. *Beaters, Shape Changers, and Complex Peaks*

We suggested above that beaters, shape changers, and complex peaks may all be different manifestations of more or less the same physics, that of latitudinal differential rotation and/or spot evolution. The beaters, shape changers, and complex peaks are highlighted separately in the CMD in Fig. 13 and the P vs. $(V - K_s)_0$ diagram in Fig. 14. All of these classes dominate the slow sequence at $1.1 \lesssim (V - K_s)_0 \lesssim 3.7$. The beaters make a larger excursion down into the fast rotating sequence with $(V - K_s)_0 \gtrsim 5.0$ than the shape changer or complex peak classes, and the shape changers seem to dominate the ‘disorganized’ region with $3.7 \lesssim (V - K_s)_0 \lesssim 5.0$. This is consistent with various manifestations of spot/spot group evolution and/or differential rotation. Especially for those shape changers (like Fig. 2 or Fig. 5) where one can see the spot evolution on timescales of the K2 campaign, the spot evolution is so slow, or the latitudinal differential rotation is so weak that spots at different latitudes have very similar rotation rates, the K2 campaign is not long enough to distinguish that second frequency. If the ‘disorganized region’ is a transition from strong differential rotation/fast spot evolution to solid body rotation/a more stable spot or spot group, then this is consistent. Moreover, there seem to be two populations in the ‘disorganized region’, fast and slow rotators; there is a gap near 1d. The slower rotators are more likely to be shape changers than the fast rotators, again consistent with the faster rotators being solid-body rotators.

5.2. *Double-dip LCs*

On the whole, the double-dip LCs above are found throughout Fig. 14 (for $(V - K_s)_0 > 1.1$), with no particular preference for color or rotation rate. This is consistent with our interpretation of them as spots on well-separated

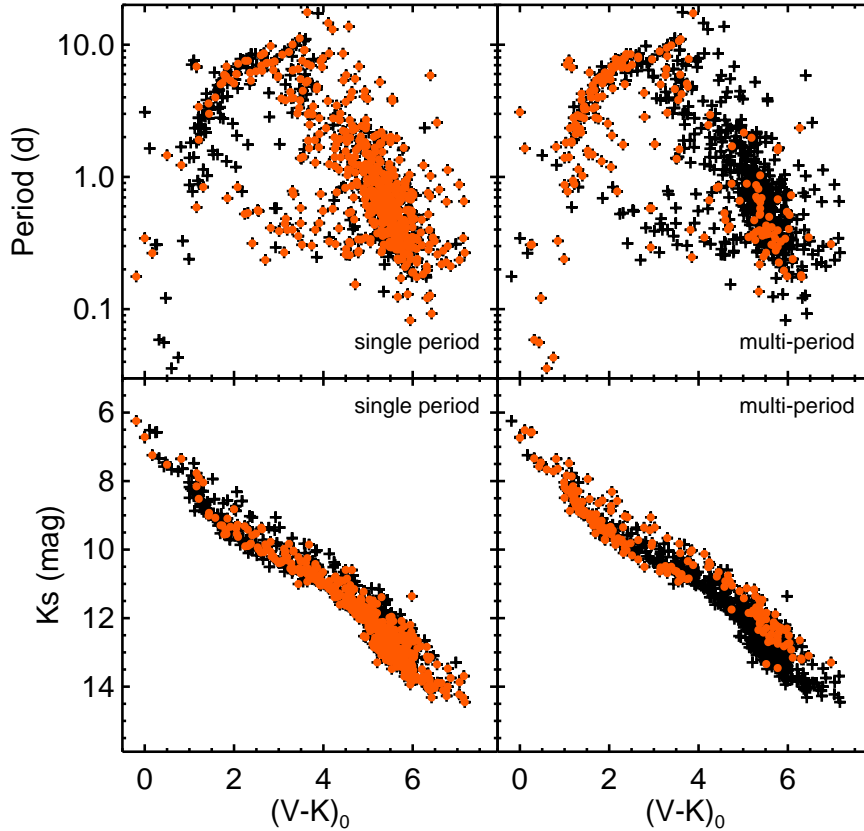


Figure 12. Plot of P vs. $(V - K_s)_0$ (top row) and K_s vs. $(V - K_s)_0$ (bottom row) highlighting the single-period (left) and multi-period (right) populations. Most of the multi-period stars are earlier-type stars, and the slow sequence is dominated by multi-period stars. The fast sequence is dominated by single-period stars. Those stars in the fast sequence that are multi-periodic also tend to be the photometric binaries, suggesting that most of the M stars have single periods, and may therefore be rotating as solid bodies.

longitudes – the effect can occur whenever there are spotted stars, with no preference for color or rotation rate. However, those that show changing shapes over the K2 campaign (moving double-dip) are distinctly higher mass than those that show no shape changes (stationary double-dip). This is consistent with our proposed interpretation of spot evolution/migration over the K2 campaign for the moving double-dip. The lower-mass stars are more likely to be rotating as solid bodies.

5.3. Resolved Peaks

For the power spectra where we can resolve the specific periods in either close or distant pairs, there is probably more than one physical explanation underlying this observed property.

Fig. 14 shows that the population with close peaks in the FGK stars seems also to track the slow sequence again consistent with differential rotation. However, in the fast sequence of M stars, there are also many more close peaks than the beater/shape changer/complex peak category. As can be seen in Figs. 13, by the M stars, essentially all of the close resolved peaks are likely photometric binaries. This possibility is explored in more detail in Paper III.

The distant peaks seem to represent a more dispersed population in both Figs. 13 and 14, less consistent with the large-scale structure in Fig. 14. Both of these characteristics would be consistent with the distant peaks being more likely to be binaries as opposed to differential rotation or spot evolution. The population of late-type multi-period photometric binaries from Fig. 12 are largely the resolved close periods, though some beaters and resolved distant periods are also photometric binaries in this color range. For the distant peak stars, because the peaks are so widely spaced in period, forcing the peaks to be differential rotation would require an unphysically large shear. The most extreme case is 210930791/BPL72, an M star, with two periods of ~ 19 d and ~ 1.7 d; a more typical period difference for the resolved distant category is ~ 1.4 d.

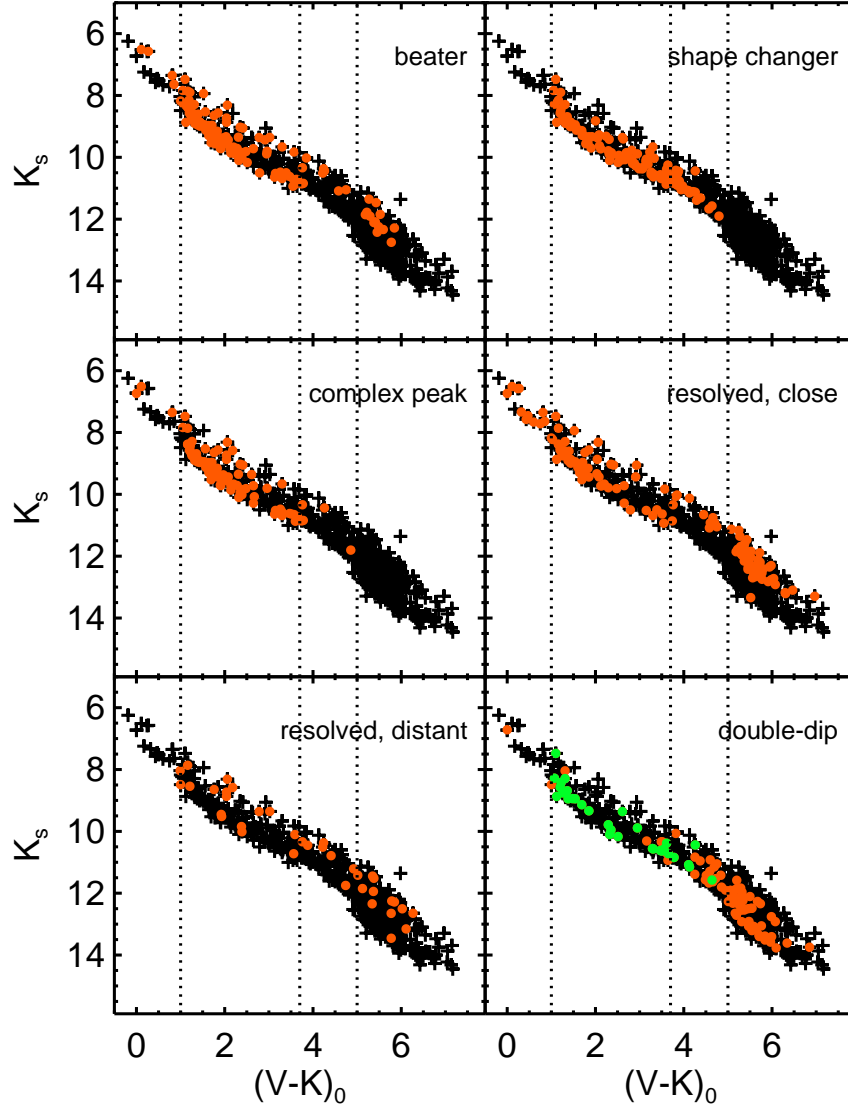


Figure 13. Plot of K_s vs. $(V - K_s)_0$, highlighting several of the LC categories described in the text. In each case, black crosses are the ensemble, and colored points highlight those objects of the category indicated. In the last panel, orange dots = stationary double-dip, and green dots = moving double-dip. The bluer stars (slow sequence) include most of the beaters, shape changers, and complex peaks, and a significant number of the resolved close peaks. Resolved close peaks are also found in the redder stars (fast sequence), and these are largely the photometric binaries from Fig. 12. Some beaters and resolved distant peaks are also photometric binaries. The double-dip LCs above are found throughout this diagram, but those showing movement within the campaign are distinctly higher mass. The dotted vertical lines are at $(V - K_s)_0 = 1.1, 3.7, \text{ and } 5.0$, the divisions between the F stars (<1.1), slow sequence (1.1 to 3.7), the ‘disorganized region’ (3.7 to 5.0), and the fast sequence (>5.0); see Papers I and III.

6. ΔP DISTRIBUTIONS

As described in Sec. 3.4 above, for stars with at least two periods, we calculated a metric, $\Delta P/P_1$, which is the difference between the closest two periods in the periodogram, divided by the primary period. Figure 15 shows the relationship between this metric and period. The division between close and distant peaks at $\Delta P/P_1 = 0.45$ can be seen there; there are some stars with both close and distant peaks. Pulsators (the δ Scutis) are often outliers in this diagram. (The possible γ Dors, having periods comparable to the rotation periods, are not outliers in this diagram.)

The linear feature in the lower right of Fig. 15 is composed of beaters and complex peaks, *e.g.*, likely attributable to differential rotation. Most shape changers and double-dip stars are single-period stars, so few of them can appear

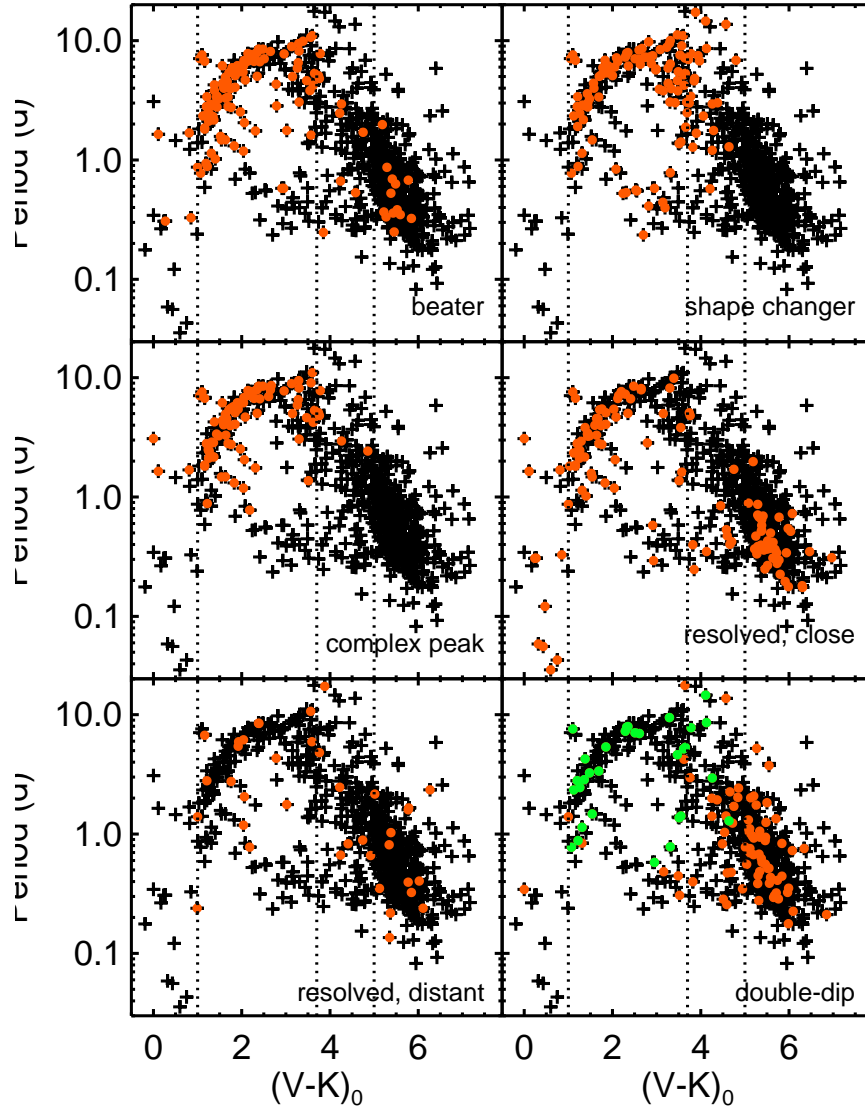


Figure 14. Plot of P vs. $(V - K_s)_0$, highlighting several of the LC categories described in the text. Notation (and the location of the dotted vertical lines) is same as Fig. 13. The slow sequence consists of beaters, shape changers, complex peaks, and resolved close peaks. Resolved close peaks are also found in the fast sequence, and these are largely the photometric binaries from Fig. 12. Some beaters and resolved distant peaks are also photometric binaries. The double-dip LCs above are found through this diagram, but those showing movement within the campaign are distinctly higher mass.

in this diagram, but those that do are found throughout this diagram. While there is scatter, most of the stars in the linear feature in the lower right of Fig. 15 become the slow sequence in the P vs. $(V - K_s)_0$ plot, and most of the multi-period stars in the slow sequence in the P vs. $(V - K_s)_0$ plot populate the linear feature in the lower right of Fig. 15.

The concentration of sources near $P \sim 0.4$ and $\Delta P/P_1 \sim 0.3$ in Fig. 15 largely populates the M star fast sequence in the P vs. $(V - K_s)_0$ plot. These fast rotating M stars are, as we have seen above, likely to be solid body rotators. Thus, these stars for which we can derive a second period are likely to be binaries. They lie in a different portion of Fig. 15 than the stars likely to be differentially rotating. For completeness, we note that a few of the fast-rotating K stars are also located in this $P \sim 0.4$ and $\Delta P/P_1 \sim 0.3$ clump.

For $(V - K_s)_0 < 4$, the most likely physical explanation for the stars with close, resolved peaks is that the two peaks are associated with spots or spot groups at different latitudes on the star, and that the star has significant latitudinal

differential rotation. Within this linear feature, the faster the rotation rate is, the closer the peaks are, suggesting weaker differential rotation in faster rotators – consistent with the fastest rotators (those that do not appear in this plot because they do not have multiple peaks) rotating as solid bodies.

The surface of the Sun rotates differentially, with a relative shear α (where $\alpha\Omega_{\text{eq}} = (\Omega_{\text{eq}} - \Omega_{\text{pole}})$) of 0.2; that is, the pole rotates 20% more slowly than the equator. If one assumes that the full range (pole to equator) could be measurable in these LCs, $\Delta P/P_1 \sim 0.5$; if one takes only the range over which sunspots are found, $\Delta P/P_1 \sim 0.2$. So, the Sun in Fig. 15 lies more or less along the extension of the slowly-rotating sequence of stars. Reinhold, Reiners & Basri (2013) have analysed data from the original Kepler field for active low mass stars, and also find a good correlation between α and rotation period, though with much more scatter than we see in the Pleiades (their sample of field stars is much less homogeneous in age and metallicity than our sample).

Reinhold et al. argue that the sloping lower bound to the points in their figure is primarily an observational bias – they simply could not resolve two peaks in the LS periodogram if those two periods would place them below that lower bound. The lower bound to the linear feature in Fig. 15 is probably also largely an observational bias for our data. We created a grid of synthetic models with known, noise-free, sinusoidal periods of comparable amplitude to test the limits of our approach to resolve the constituent periods. Under these conditions, it becomes harder to resolve periods below the linear feature. Recovery of the two periods is not precluded, but it becomes less likely, as the relative amplitudes and phasing of the constituent periods becomes more important.

However, no such detection bias exists immediately above the linear feature in our plot, from which we infer that for a coeval, young population there is a well-defined degree of differential rotation at a given mass, at least once the star is part of the slowly-rotating sequence.

Recently, Balona & Abedigamba (2016) find a similar relationship for differentially rotating stars in the main Kepler field. They find that $\Delta\Omega/\Omega$ as a function of Ω decreases sharply with rotation rate; transforming Fig 15 to that parameter space finds that our linear feature is consistent with their derived relationship.

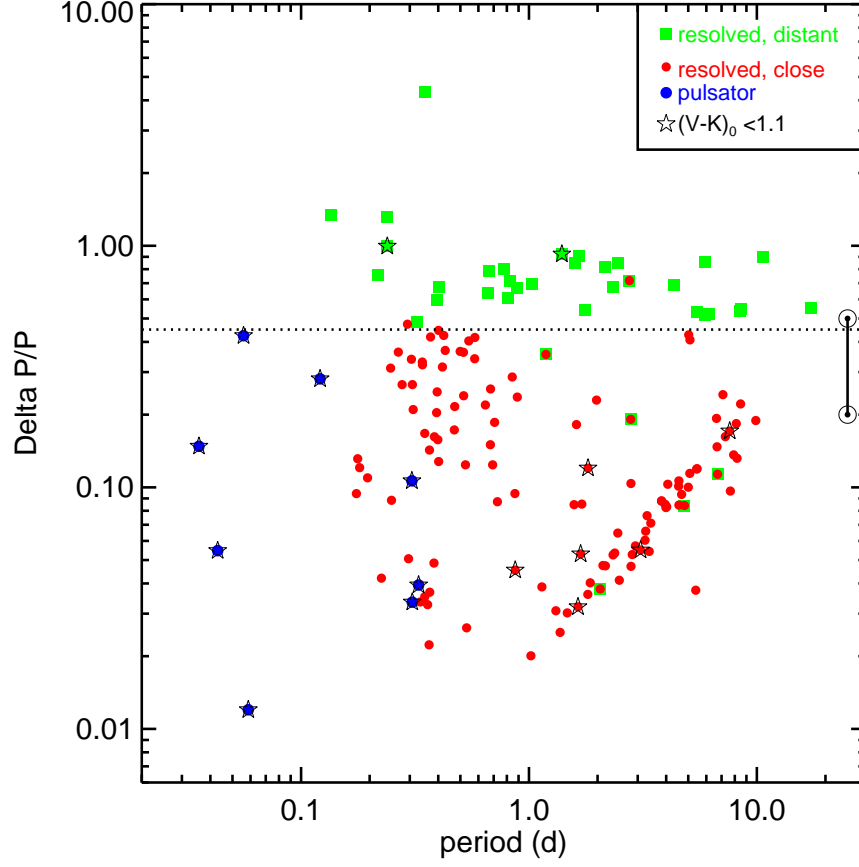


Figure 15. Plot of $\Delta P/P_1$ vs. P for pulsators (blue dots), resolved distant peaks (green squares), and resolved close peaks (red dots). An additional black star indicates that those stars have $(V - K_s)_0 \leq 1.1$ (see Paper III). The range of possible values for the Sun is included for reference (\odot); if one takes as ΔP the range of periods measured where sunspots occur, $\Delta P/P_1 \sim 0.1 - 0.2$, but if one takes the full range of ΔP , equator to pole, $\Delta P/P_1 \sim 0.5$. The dotted line is at $\Delta P/P_1 = 0.45$ and denotes the boundary between close and distant resolved peaks. Some objects are tagged as both close and distant peaks (*e.g.*, there are at least 3 periods in these objects, two of which are close and a third of which is not close). Pulsators (δ Scutis) are largely outliers. The linear feature in the lower right predominantly becomes the slow sequence found in the P vs. $(V - K_s)_0$ plot. The clump of sources near $P \sim 0.4$ and $\Delta P/P_1 \sim 0.3$ becomes the M star fast sequence in the P vs. $(V - K_s)_0$ plot. The lack of sources below the linear feature is largely an observational bias.

7. CONCLUSIONS

We have continued our analysis of the K2 Pleiades lightcurves, finding complicated multi-period behavior that we have grouped into categories. About 24% of the sample has multiple, real frequencies in the periodogram, sometimes manifesting as obvious beating in the LCs. These LCs can fall into categories of those having complex and/or structured periodogram peaks, unresolved multiple periods, and resolved multiple periods. These are likely due to latitudinal differential rotation and/or spot/spot group evolution. About 13% of the sample seems to have one period in the power spectrum, but the light curve is seen to undergo substantial changes over the K2 campaign. These may be cases where the spot/spot group evolution is slow over the 72 day K2 campaign, or cases in which the latitudinal differential rotation is so weak that 72 days is not enough time to separate the nearly identical periods. About 1% of the sample are multi-period because they are likely δ Scuti pulsators. About 12% of the sample have double-dipped or (double-humped) light curves that redistribute power into peaks in the power spectrum other than the main period. These light curves are probably a result of spots on well-separated longitudes on the star. In 6 cases, the light curves have stable, shallow, angular patterns in the phased LC that affect a relatively small fraction of the phase coverage. These shallow flux dips may be due to transits or eclipses of orbiting clumps or clouds near the Keplerian co-rotation radius.

There are correlations of these broad categories with location in the P vs. $(V - K_s)_0$ diagram. The slow sequence is dominated by complex and/or structured peaks, unresolved multiple periods, and resolved multiple periods; latitudinal differential rotation is likely to be happening in these higher-mass stars. The fast sequence is dominated by single-period stars; these are likely to be rotating as solid bodies. The transition between the fast and slow sequence is dominated by the shape changing LCs. Multiple period identifications among the lower mass stars are likely to be binaries. Some multiple period identifications among the higher mass stars may be multiples or even pulsation, but the P we have chosen is the one we believe to be closest to the rotation period (that for the primary at least), so this ambiguity is unlikely to affect our results.

For those stars where we can detect at least two periods, we can calculate $\Delta P/P_1$, which is the difference between the closest two periods in the periodogram, divided by the primary period. In the plot of $\Delta P/P_1$ vs. P_1 , there is a striking linear feature in the lower right. It is composed of stars whose LCs are categorized as beaters and complex peaks, and they become the slow sequence in P vs. $(V - K_s)_0$. While non-detection of periods below this linear feature is likely an observational bias, no such bias affects the distribution above the linear feature. Given that, there is a well-defined correlation between the degree of latitudinal differential rotation and period for our sample.

We continue discussion of these results in Paper III (Stauffer et al. 2016), which speculates about the origin and evolution of the period distribution in the Pleiades.

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Facility: Kepler

Facility: K2

Facility: Spitzer

Facility: 2MASS facilityIRSA facilityNASA Exoplanet Archive facilitySimbad facilityVizier

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