KEPLER AND THE LONG-PERIOD VARIABLES

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ABSTRACT

High-precision Kepler photometry is used to explore the details of asymptotic giant branch (AGB) light curves. Since AGB variability has a typical timescale on the order of a year, we discuss at length the removal of long-term trends and quarterly changes in Kepler data. Photometry for a small sample of nine semi-regular (SR) AGB stars is examined using a 30 minute cadence over a period of 45 months. While undergoing long-period variations of many magnitudes, the light curves are shown to be smooth at the millimagnitude level over much shorter time intervals. No flares or other rapid events were detected on a sub-day timescale. The shortest AGB period detected is on the order of 100 days. All the SR variables in our sample are shown to have multiple modes. This is always the first overtone, typically combined with the fundamental. A second common characteristic of SR variables is shown to be the simultaneous excitation of multiple closely separated periods for the same overtone mode. Approximately half the sample had a much longer variation in the light curve, likely a long secondary period (LSP). The light curves were all well represented by a combination of sinusoids. However, the properties of the sinusoids are time variable, with irregular variations present at low levels. No non-radial pulsations were detected. It is argued that the LSP variation seen in many SR variables is intrinsic to the star and linked to multiple mode pulsation.

Key words: methods: data analysis – stars: AGB and post-AGB – stars: variables: general

Online-only material: color figures, supplemental data

1. INTRODUCTION

The General Catalogue of Variable Stars (GCVS) lists multiple groups of pulsating variable stars of late spectral type with periods of several tens of days or longer. While historical divisions by period and spectral type were made in the absence of knowledge about stellar evolution, we now recognize that these long-period variable (LPV) stars are evolved low- and intermediate-mass stars. During the red giant branch (RGB), asymptotic giant branch (AGB), and post-AGB phases, stars are characterized by highly extended stellar envelopes providing the basis for long-period pulsation.

The variability timescale of LPVs requires monitoring over years to decades to properly describe the light changes. In the 1990s, long-term, rapid cadence monitoring of variable stars in selected fields occurred as a byproduct of ground-based photometric surveys searching for microlensing events. This data was transformative, providing large data sets of high-quality light curves for stars in the Magellanic Clouds (Wood et al. 1999; Lebzelter et al. 2002; Kiss & Bedding 2003; Ita et al. 2004). The Magellanic Cloud variables are at a known distance, and hence have known luminosities, permitting the construction of period–luminosity (P–L) diagrams for a large sample of late-type stars. While previously a P–L relation had been known for large-amplitude LPVs, the Miras (Glass & Evans 1981), P–L relations for all late-type variables are apparent in the LMC data (Soszyński et al. 2009).

In this paper, we focus on those LPVs that are luminous, with periods of ~100 days or longer, but are not Miras. In the parlance of the Wood et al. (1999) P–L relation, these are sequence C and C' (Soszyński & Wood 2013). In the classical variable star nomenclature, these are semi-regular (SR) variables. The GCVS classification is unfortunately blurred across a large range of temperature and luminosity with SR variables found across a large part of the cool star P–L diagram. Here, we will discuss those that have AGB luminosity. Other recent papers have discussed SR variables that are less luminous and are on the RGB (Christensen-Dalsgaard et al. 2001; Stello et al. 2014).

The improved P–L diagram results in new astrophysical challenges. The C and C' variables are pulsating radially in the fundamental mode, a low overtone mode, or a combination of modes. The origin of AGB SR behavior, both in cycle length and amplitude, remains unclear, but their light curves can in some cases be reproduced by the combination of several periods (e.g., Kiss et al. 1999; Kerschbaum et al. 2001). The major challenge, however, is an explanation of the long secondary periods (LSPs) found in many of the overtone pulsators. With a typical timescale of several hundreds to thousands of days, the secondary periods are significantly longer than the fundamental mode periods and therefore cannot be explained by radial pulsation. Various solutions have been discussed, but a satisfactory explanation has yet to be found (e.g., Nicholls et al. 2009).

One route to further understanding of these stars is precision continuous photometric monitoring. Recent studies faced the typical problems of ground-based observations: time series of very limited length and limited photometric accuracy, and observational gaps resulting from both diurnal and seasonal cycles. A space mission obtaining photometry continuously over a time span of several years is, therefore, clearly relevant. One of the many side benefits of the Kepler mission5 was the opportunity to obtain long and precise time series of variables,

5 http://kepler.nasa.gov/
including LPVs with uninterrupted sampling extending over months.

Banyai et al. (2013) presented the first extensive study on the variability of both RGB and AGB M giants using the long and continuous light curves provided by Kepler. In that paper, the authors focused on the global characteristics of the light variations of these cool giants. Their study confirmed the presence of several pulsation modes based on the patterns seen in the Petersen diagram, and it revealed a clear distinction between solar-like oscillations and large amplitude, mira-like pulsations. This transition seems to appear at log $P$(days) $\sim$ 1.

The Kepler mission was optimized to search for planet transits, not slow variations spanning weeks to years. As a consequence, the aim of our paper is twofold. In the first part, we investigate the applicability of the Kepler data products to the construction of long-baseline light curves by combining individual data sets of three months length. We will focus on a small sample of 12 stars, 3 of which have small amplitudes that are included especially to identify instrument-specific effects. The light curves are then used in the second part of the paper to discuss the light change of SR variables on the basis of these uninterrupted and photometrically precise light curves.

2. THE SAMPLE

The definition of the SR variable class limits the visual amplitude to less than 2.5 magnitudes. The Mira variables are defined as having a visual amplitude in excess of 2.5 magnitudes. Thus, the SR class excludes the large amplitude, AGB-tip variables. The intent of our survey was to study AGB SR variables over as full a range of variability as possible. Unfortunately, most SR variables have not been extensively studied in the past. The better known objects have been assigned a subclass a or b reflecting a more or less regular light curve. However, many late-type stars have time series of ground-based photometry that are too short or otherwise inadequate to classify the variability. The SRb class has been associated with the LSP phenomenon. A sample spanning these variability classes was of special interest with the goal of seeing if actual differences existed between the subclasses.

GCVS (Samus et al. 2012) list of variables in Lyrae and Cygnus was searched for late-type SR variables in the Kepler field. Other surveys, for instance the ASAS catalog (Pigulski et al. 2009), sample a much shorter time interval and were less useful in selecting a variety of variables. The two brightest SRs in the Kepler field are AF Cyg, an SRb with spectroscopically and photometrically studied LSP (Hinkle et al. 2002), and AW Cyg, a carbon-rich SRb variable. Observation of these two bright stars required special target pixel masks and hence they were not included in our original target list. However, Banyai et al. (2013) selected AF Cyg as a target and developed a special pixel mask. We included that data. To represent the SRa class, we identified V588 Lyr, V1670 Cyg, and V1766 Cyg. For the SRb class, V1953 Cyg, EG Lyr, and BU Lyr were selected. We included two SR stars without sub-classifications, V1253 Cyg and V2412 Cyg.

Three low-amplitude variable stars located in the field of the old open cluster NGC 6791 were analyzed to test the reduction process. The stars have periods in the range 10–20 days (Mochejska et al. 2003, 2005; Bruntt et al. 2003; De Marchi et al. 2007) with amplitudes of less than 0.1 magnitude. The brevity of the ground-based NGC 6791 survey results in fairly uncertain periods. The GCVS (Samus et al. 2012) classifies the test stars as red giants with SR periods, i.e., stars that are likely members of sequence A or B in the LPV L–P diagram. The spectral types are correspondingly earlier than for the program stars, with the test stars probably on the RGB.

Spectroscopy was carried out to determine the spectral types for the brightest program stars. The observations were made at the Kitt Peak National Observatory using the four-meter Mayall telescope in 2011 May and the Coude Feed telescope in 2010 October, 2011 March, and 2011 May. The resulting spectral type classifications can be found in Table 1. When possible, these are compared to the classifications found in the GCVS. V616 Lyr was observed with the four-meter only, V588 with both the four-meter and the Coude Feed, and the other observations are from the Coude Feed. Spectral types and luminosity classes were assigned based on Jacoby et al. (1984).

The spectral types for V616 Lyr, V588 Lyr, V1766 Cyg, and V1953 Cyg are presented here for the first time. Our work compares favorably with the types in the GCVS for EG Lyr. However, we classified BU Lyr as M4-M5 III while the GCVS lists it as an M7 star. This could result from changes in the spectral type with the pulsation phase. This has been reported for semiregular variables by Percy (2007). Phase-dependent changes can be mitigated by repeated observations. EG Lyr, BU Lyr, and V1766 Cyg were observed on two or more dates separated by several weeks or months.

Six stars in Table 1 were too faint on the dates of our observations for spectroscopic work. Spectral types were derived from V-K colors. The reddening is not known for these stars, so the corresponding spectral temperatures are likely to be too cool. These data show that all the program SR stars are, as expected, M stars (Table 1). The low-amplitude test objects (Table 1) are earlier spectral types.

3. KEPLER DATA AND ANALYSIS

The Kepler Space telescope has an effective aperture of 0.95 m, a primary mirror with a 1.4 m diameter, and a field of view of 105 deg$^2$. It was positioned in an Earth-trailing heliocentric orbit with a 372.5 day period. The data discussed here are from the original Kepler mission to observe a section of the Cygnus region along the Orion arm centered on galactic coordinates (76.32°,+13.5°) or RA = 19:22:40,
Details can be found in the Kepler Archive Manual. Here is a brief summary of the data typically available for a star observed with Kepler.

1. Simple Aperture Photometry (SAP): In the Kepler Asteroseismic Science Consortium (KASC) archive, these data are called RAW. The SAP data come with no correction of differences in the flux zero point between the quarterly observation blocks. Such differences stem from changes in the CCD pixels used, the use of different target masks, changes of the seasonal thermal conditions causing focus changes, and changes of the zodiacal light.

2. Pre-search Data Conditioning (PDC or PDCSAP): These are preliminary light curves provided by the Kepler Science Operations Center Science Processing Pipeline. To search for transiting planets, various errors including systematic errors are corrected, flux outliers removed, and data gaps partially filled. The pipeline producing the PDC data removes all long time trends, so these data are of limited use for the analysis of LPVs.

3. Target Pixel Data (TPD): The TPD deliver flux information for each pixel in the window on the CCD used to obtain the star’s brightness. The size of the window is neither the same for all stars nor necessarily constant for a given object. Formats between 4 × 3 to 13 × 59 pixels have been found for our sample stars. For the bright target AF Cyg, a maximum window size of 15 × 587 pixels was used.

4. Superstamps: For two areas in the Kepler field, around the open clusters NGC 6791 and NGC 6819, a complete image is provided in LC mode. These “superstamps” are provided with the same sampling frequency as the TPD data.

5. Full-Field Images: These were taken monthly at the end of an observation cycle.

Corrected flux light curves by the KASC working groups using their own specific pipelines for the data reduction are sporadically available.

3.1. Removing Instrumental Effects

3.1.1. Cotrending

To examine the shorter period astrophysical signals, the instrumental effects that dominate the light curves first must be removed. In addition to zero-point differences (above) there are also trends in the flux values within a quarter. One technique for removing these effects is “cotrending,” described in detail by Smith et al. (2012), and based on the identification of common trends in a selected set of light curves on a given chip. Cotrending is most effective at removing instrumental signals while preserving astrophysical signals for periods of a few tens of days. For the LPVs in our set, with typical periods generally greater than 100 days, limitations of the cotrending algorithm preclude reliable results. The alternative way is to leave the trends in the light curve and try to identify and remove them during the period search.

Tests with low-amplitude variables show that the first three cotrending basis vectors for each individual quarter result in a good match to the instrumentally dominated overall shape of the light curve and the thermal features. This gives us confidence that cotrending is removing instrumental effects but not introducing significant errors into the light curve. Introduction of the fourth and fifth basis vectors starts to show overfitting of the light curves and loss of astronomical signal. However, once the individual quarters have been cotrended, a significant difference between the median flux levels for each quarter remains. A significant limitation of cotrending for the LPV Kepler light curves lies in preserving and identifying very long-period variations where the method typically results in ambiguous conclusions.

3.1.2. Linking the Quarters

In contrast with other variable classes, the study of long-period variables with Kepler requires a very precise linking of the various quarters. Errors introduced in linking the quarters can have a major impact on the derived long periods and their amplitudes. Unfortunately, this linking is hampered by the gaps of 0.9–3 days in time coverage that occur between the quarters. In some cases where the star has not been observed continuously in all quarters, very large gaps can occur. Therefore, we focused in our study on the various approaches to close the gap between the quarters correctly and, if possible, in an objective, unambiguous, and easily reproducible way.

First, we consider SAP data. A first simple approach is to simply stick together the various quarters starting with the first one, always using the flux of the last data point of the previous quarter and the first data point of the following quarter. If cotrending was applied first, scaling of each quarter to the same median level can be used to reduce the discontinuities between the quarters. This approach is particularly helpful for faint targets where the increased scatter in the light curve complicates the scaling.

One source of the differences in the flux levels stems from the variable mask sizes used to extract the photometric data for the SAP light curves (Garcia et al. 2011) and the quarterly change of the CCDs and their different characteristics. Fortunately, the Kepler archive also includes TPD that allow one to check the automatically chosen mask for an individual star. As mentioned above, the size of the mask is not constant for the four quarters and is not always covering the target correctly. For illustration, we present some example TPD around the star V621 Lyr (KIC 2570059) in Figure 1. In the four quarters Q6–Q9, we see a shift of the expected center of the star indicated by the black cross and the actual central pixel. Consequently, the target mask, indicated by red squares, does not include the star’s center. Therefore, neither the SAP nor the PDC light curve show the correct light variation of this star. Using TPDs, we could correct this mismatch, and by extracting the data from missing pixels in Q6 and Q9 from the superstamp

http://archive.stsci.edu/kepler/manuals/archive_manual.pdf
we could even complete the TPD data set. Furthermore, we also extracted and added the missing quarters Q2–Q5 and Q10–Q13 to get a much longer time coverage for this star.

As a consequence of these mismatches, we decided to use a flexible aperture, introducing a threshold value to select the pixels included for each individual observation. The threshold value was based on the flux of pixels not belonging to the star, which typically have significantly lower values and show almost no variation. Depending on whether or not the star’s position is in a crowded field, threshold values between 45 and 220 e⁻¹ s⁻¹ give the best results. In the case of the example shown in Figure 1, we see that there are four to eight more pixels significantly contributing to the total light, compared with the Kepler default target aperture. A careful definition of the aperture is therefore of critical importance to avoid systematic errors in the photometric data. Our approach permitted us to reduce strongly the influence of the telescope jitter on the extracted light curve. Figure 2 compares the result of our approach using TPD and the SAP data directly from the archive with and without amplitude rescaling.

Linking of the various quarters unambiguously can also remain a challenge in the case of the TPD data. A simple connecting, as described above, can lead to results that are likely incorrect. This problem occurs primarily for the gap between Q7 and Q8, which is much larger than the typical ones lasting for more than 15 days. Here, we use the light curve shape from the nearby cycles shifted to lie over the gap to estimate the needed adjustment immediately after the gap.

The various sources producing the offset between quarters are a mixture of multiplicative and additive contributions that cannot be disentangled. To estimate the resulting range of uncertainty, we tested both approaches, i.e., a purely multiplicative and a purely additive correction. For the period determination, both methods give about the same results, but the amplitude variations are naturally different. For a low-flux star like V621 Lyr, the amplitude difference between rescaling using a multiplicative factor or using an additive constant is about ±2%, whereas for a highly variable and high-flux object like V1766 Cyg, we notice changes of up to 3.76%. In the following, we assume that the major effects are of multiplicative nature and use this for scaling.

While the TPD achieves a better result, in some cases problems can still occur. For instance, for Q6–Q9, the row of pixels adjacent to the center of V621 Lyr is missing in the TPD data. In such cases, the superstamps discussed in the next paragraph can provide a solution. Data for missing TPD observations also can be recovered from the superstamps. The superstamps for NGC 6791 consist of 20 images of 100 × 20 pixels in the format of the TPD at the 29.4 minute LC intervals. Several of our targets in the constellation Lyra have superstamp data available. We used these data to close gaps in the time coverage of the SAP and TPD light curves. To make sure we can combine the superstamp data with the other data sources, we extracted quarter 10 data of V607 Lyr, where we also have TPD data for the same time. The agreement is excellent.

One disadvantage of this method lies in the TPD-like structure of the superstamp data. For one complete set of 100 × 20 pixels, only one quality flag is available, and in many cases it shows values far above the good quality limit of 1000. For the TPD analysis, we ignored all observations with non-zero quality flags. For the superstamps, the same restriction results in just a handful of observations in a quarter. An acceptable solution was found by accepting observations with a summed up quality flag of up to 9000 and adding some additional formal checks. For instance, we remove data with zeros in the
date or flux and extreme outliers identified by a two-point difference function. A few obviously wrong data that were still in the light curve after these checks had to be removed manually.

Our analysis revealed that the best way to construct complete and reliable light curves from the Kepler data for LPV is to apply a mix of methods combining various types of data provided in the Kepler archive. In contrast to the work of Banyai et al. (2013), we use TPD data instead of SAP data in our analysis.

3.2. Light Curve Analysis

3.2.1. Fourier Methods

As a primary period search method, we used classical Fourier analysis combined with a least square method optimization provided by the Period04 software package (Lenz & Breger 2005). The search was limited to a maximum frequency of 0.2 cycles per day (c d$^{-1}$), i.e., a lower period limit of five days. Up to four periods were used to fit the light change. While this upper limit for the number of periods included in the model fit was set somewhat arbitrarily, it was well motivated by our experience, that including further periods usually does not lead to a significant improvement of the fit. Furthermore, in many of our sample SRVs, we observed a clear drop in the signal-to-noise ratio (S/N) for additional periods in the Fourier power spectrum (see also Table 3). However, the existence of further significant periods cannot be totally excluded. The Fourier analysis was performed on the light curves without co-trending.

3.2.2. Autocorrelation

In addition to Fourier analysis, other methods have proven useful in light curve analysis, revealing additional information beyond the periods present in the light curves (Templeton 2004). For stars with part of the fundamental group description including irregularities in the light curve, autocorrelation and related self-correlation methods have been found to be useful in quantifying the cycle-to-cycle variation in addition to the finding the dominant period (Percy & Mohammed 2004; Percy et al. 2009). A regularly periodic light curve will have strong correlations for time lags that are multiples of the period, with the strength of the peak correlation staying high over many cycles. SR stars will generally have a strong correlation for the first few multiples of the period, but the coefficient drops off over time. The persistence of the autocorrelation can then be used as an indicator of the regularity present in a SR star. Light curves that have multiple periods will tend to have weaker autocorrelation peaks, although there can be complex patterns emerging from the beat phenomena between the dominant periods.

We performed an autocorrelation analysis based on the algorithm of Box & Jenkins (1976). The traditional autocorrelation routine requires a perfectly evenly spaced time series; therefore, we used an autocorrelation routine adapted for astronomical time series developed by Matthew Templeton (2009, private communication) at the AAVSO. For the longer-period SR stars, we used a lag timing step of 0.5 days and maximum lag times up to 1000 days. While lag times larger than half of the total data range have more limited accuracy, we include these longer lag times for some stars as an indication of the possible longer term behavior, but always recognizing that the accuracy is diminished. The autocorrelation coefficient can range from +1.0 for a perfectly correlated signal to −1.0 for a perfectly anti-correlated signal (Templeton 2004). In this analysis, we consider a strong correlation to be one with a peak coefficient above 0.75, while levels below 0.25 are classified as a weak correlation. In our analysis of these stars, the periods found using autocorrelation are generally in agreement with the periods found through Fourier analysis, but we additionally comment on the regularity in the light curves as measured through the strength and persistence of the autocorrelation coefficient.

3.3. Test Sample

The resulting periods (numbers of brackets give the S/N derived from the Fourier analysis) and supplemental data for each star are listed in Table 2. In the text, we will refer to the periods as P1–P4, listed left to right in the tables, with P1 having the largest amplitude. Transformation of Kepler fluxes into Kepler magnitudes was performed using the relation given on the Kepler webpage.7

Previous analyses of Kepler data (e.g., Banyai et al. 2013) identified a signal with a length of approximately one year in most light curves. This so-called Kepler year of 372.5 days length has an origin that has not been fully explained. It is obviously related to the orbital motion of the satellite. Focus changes due to a varying satellite temperature are a possible cause.8 This could be augmented by seasonal variations of the background zodiacal light. The Kepler year is prominent in our test sample variables, which have low amplitudes. However, for the program stars, all of which have large amplitudes, the Kepler year has either a minor impact or could not be detected at all. We performed additional test reductions on stars in Figure 5 of Banyai et al. (2013) showing the Kepler year. Using TPD data instead of SAP data, the Kepler-year variations disappeared in five of eight stars and thus could be partly an artifact introduced by the SAP reduction pipeline. A detailed

\footnote{http://keplerscience.arc.nasa.gov/CalibrationSN.shtml} 
\footnote{Kepler Data Release Notes 14: https://archive.stsci.edu/kepler/release_notes/release_notes14.}
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Table 2

| Kepler ID | GCVS Name    | GCVS Period (d) | P1 (S/N^a) | P2 (S/N) | P3 (S/N) | P4 (S/N) |
|-----------|--------------|----------------|------------|----------|----------|----------|
| 2437359   | V616 Lyr     | 20.9           | 370.11 (8) | 189.10 (1) | long     | 16.5 (1) |
| 2569737   | V607 Lyr     | 9.6            | 371.31 (14)| 185.36 (6)| 487.38 (4)| 13.54 (3)|
| 2570059   | V621 Lyr     | 10             | 365.31 (7) | 841.3 (3) | long     | …        |

^a S/N of the peak in Fourier power spectra.

investigation of this difference could shed more light on the origin of this feature in the Kepler light curves but is beyond the scope of this paper.

3.3.1. V616 Lyr = NGC 6791 V73 = KID 2437359

A combination of a long trend (>5000 days) and P1 = 370.11 days, resulting from Fourier analysis, gives an excellent fit to the light curve (Figure 3). Adding P2 = 189.1 days, which is approximately half the value of P1, gives a visible improvement. However, P1 is very close to the Kepler year and P1 and P2 are almost certainly not intrinsic variations of the star. Cotrending was very effective in removing this long period. Also obvious in the data is a very short period of ~16 days. Mochejska et al. (2003) and Bruntt et al. (2003) found similar periods. Autocorrelation and Fourier analysis both show that the 16–16.5 days period is not a single period. The typical full amplitude of the 16 days period variation is around 0.01 magnitudes, with the amplitude changing over time.

3.3.2. V607 Lyr = NGC 6791 V97 = KID 2569737

The strongest signal resulting from Fourier analysis is a 372 days (P1) period. The fit can be improved by adding essentially the half value of P1, P2 = 185.36 days, and P3 = 487.38 days. Since P1 is very close to the Kepler year, P1 and P2 are almost certainly not intrinsic to the star. The origin of P3 is not clear. As with V616, the data contain an obvious very low amplitude variation (P4). In the case of V607 Lyr, the period is ~13.5 days. P4 agrees with the 13.6 days period from the ground-based data of Mochejska et al. (2005) but differs from the 9.6 day value of Bruntt et al. (2003). The typical full amplitude of the oscillation is roughly 0.01 mag with the amplitude changing with time. The light curve shown in Figure 4 contains a gap over quarters 11 and 12 when it was not observed as a target aperture with Kepler. We filled that gap using superstamp data as described in Section 3.1.2. It is interesting to note that the short-period variation is much less obvious in these data. A reason for this difference is not understood yet.

3.3.3. V621 Lyr = NGC 6791 V99 = KID 2570059

The amplitude of the Kepler light curve (Figure 5) is rather small. A one-year period (365.31 days, P1) is very clear but could be identical with the Kepler year. A combination of P1, P2 = 841.3 days, and a long time trend, clearly exceeding the total length of our time series, gives a very good fit to the Kepler light curve. P2 and and the additional long time trend are not well defined. To further examine the data, we applied cotrending to the SAP light curves for the individual quarters. A satisfactory cotrend fit required the first five cotrending basis vectors in this case since the third and fourth basis vector still seemed to show some of the original unwanted thermal features. The cotrend fits matched the shape of the variations of V621 Lyr very well. Autocorrelation and Fourier analysis of the cotrended light curves reveal no significant short-period signals. The very small amplitude ~10 days variations reported by Bruntt et al. (2003) and Mochejska et al. (2005) were not present in agreement with the results published by De Marchi et al. (2007). The Kepler data for V621 Lyr contain no intrinsic variations, i.e., at the time of the Kepler mission this object was not a variable star.

3.3.4. Summary of Test Results

In the three very low-amplitude test stars, the Kepler-year artifact provides the dominant signal. Figure 6 shows the TPD light curves for the three low-amplitude test stars and the zoomed and shifted Kepler background^9 extracted from V607 Lyr. The Kepler-year periods in these stars differ by at most 2% from the nominal Kepler-year period of 372.5 days with amplitudes of less than 0.3 Kepmag. The Kepler-year signals are not in phase and all have specific Kepler-year distortions even when recorded on the same CCD. This agrees with the findings of Banyai et al. (2013) on the Kepler year.

In addition to the 372.5 day Kepler year, our data are frequently better fit by including an instrumental period of a half Kepler year and periods longer than the Kepler year. In addition, a long time trend at the 0.1 Kepler magnitude scale with a period not defined in the four years of Kepler data is seen in all three stars. In the test stars we were able to detected intrinsic periods in the range of 13–20 days with amplitudes as small as 0.005 Kepler magnitude.

4. PROGRAM STAR ANALYSIS

Here, the analysis of the individual program stars is discussed. We include brief summaries of what we know about these stars from the literature. The resulting periods and supplemental data for each star are listed in Table 3.

4.1. EG Lyr (KID 3431126)

Preston et al. (1963) found that EG Lyr had an M5 III spectrum and rejected the earlier identification as an RV Tau variable. Miller (1969) classified EG Lyr (using the alias VV 221) as an LPV with an uncertain period of 267 days. The fourth edition of the GCVS (Kholopov 1985) reclassified EG Lyr as an SRb star with a period of ~236 days. Wahlgren (1992) found the colors to be in agreement with an M6 III. The

^9 A calibrated on-flight sky background is taken from a pixel mask per CCD and the stars values are calculated by a polynomial expression (Caldwell et al. 2010). The background consists mainly of two parts: the seasonal variation of the background flux, which is due to the changing zodiacal light signal, and the additionally diffuse starlight from faint background stars (Figure 6 of Caldwell et al. 2010).
ASAS observations of EG Lyr cover about two cycles with a period roughly consistent with the GCVS value. However, ASAS classified the star as aperiodic. The Kepler data show a strong light variation (see Figure 7) but the periodicity is not obvious. The full amplitude of the oscillations, from minimum to maximum, range from about 0.2–0.8 magnitudes. In general, the peaks in the light curves are fairly narrow across the whole light curve. The minima are fairly narrow in the first half of the light curve but become much wider with evidence of greater structure in the second half of the light curve.

Three periods, $P_1 = 228.9$ days, $P_2 = 258.24$ days, and $P_3 = 137.74$ days, give a reasonably good fit and predict the times of the observed maxima and minima as well as the overall shape of the light curve. After subtraction of the periods, the residuals suggest the existence of a long time trend, considerably longer than the observed time series, and a short period with a length around 78 days but without a strict periodicity. Autocorrelation analysis similarly shows a strong correlation at 238 days with a less well resolved period at 140 days. The GCVS period of 236 days is a good match to the autocorrelation period and falls between our Fourier periods $P_1$ and $P_2$, providing overall good agreement on the period length.

4.2. BU Lyr (KID 5176879)

BU Lyr was initially identified as a variable by Ross (1928) from a one-magnitude difference in brightness measured 20 years apart. It subsequently was identified by Neugebauer & Leighton (1969) as a bright near-IR star, $K = 2.95$, with an infrared index $(I - K) = 4.39$. Zverev & Makarenko (1979) confirm that this is a very late-type star with a spectral type of M7 and a stable mean period of 259 days. The light curve appeared to have a double maximum. The brightness of the main maximum is fairly stable but the brightness and phase of the second maximum and the minima is variable. However, ASAS observations of BU Lyr show variability without a clear periodic pattern and this survey classified BU Lyr an aperiodic variable. The GCVS classifies BU Lyr as an SRb variable with a visual amplitude of 1.4 magnitude.

The Kepler light curve looks irregular (see Figure 8) but the amplitude is quite large. Typical variations are in the general range of 0.3 magnitudes with variations just over 0.5 magnitudes for the full light curve. Autocorrelation analysis suggests a weakly correlated period of about 150 days. Fourier analysis of the data set gives two periods very close together: $156.52$ days ($P_1$) and $158.90$ days ($P_2$). Adding a variation on a timescale of about one year ($P_3$) reproduces some aspects of the light curve, including the correct prediction of most of the maximum and minimum times. However, much of the shape is not properly reproduced. No clear periodicity is visible in the residuals after subtracting $P_1$–$P_3$. The double maximum structure reported by Zverev & Makarenko (1979) is not seen in the Kepler data. Instead, the brightness of the maxima and minima seems to change in an irregular way. Similarly, we do not see a 259 days period. The residual O-C over the time span of our Kepler observations suggests a tendency toward an increasing period.
Table 3
Program Star Results

| Kepler ID | GCVS Name | Period | P1 (S/N)* | P2 (S/N) | P3 (S/N) | P4 (S/N) |
|-----------|-----------|--------|-----------|-----------|-----------|-----------|
| 3431126   | EG Lyr    | 236    | 228.9 (16)| 258.2 (13)| 137.7 (5) | ...       |
| 5176879   | BU Lyr    | 259    | 156.5 (32)| 158.9 (31)| 347.5 (6) | ...       |
| 5614021   | V588 Cyg  | 116.4  | 116.4 (9) | 217.9 (9) | 198.3 (6) | ...       |
| 6127083   | V1670 Cyg | 612.7  | 612.7 (9) | 612.7 (9) | 612.7 (9) | ...       |
| 7842386   | V1766 Cyg | 113.7  | 113.7 (6) | 113.7 (6) | 113.7 (6) | ...       |
| 8748160   | V2412 Cyg | 92.5   | 92.5 (6)  | 92.5 (6)  | 92.5 (6)  | ...       |
| 9528112   | AF Cyg    | 95.2   | 95.2 (6)  | 95.2 (6)  | 95.2 (6)  | ...       |

* S/N of the peak in Fourier power spectrum.

4.3. V588 Lyr (KID 5614021)

Dahlmark (2000) identified V588 Lyr as a possible Mira of period 221 days and a range of 12.5 magnitudes to 14.0 magnitudes. The GCVS lists V588 Lyr as an SRa variable. ASAS observations found it to be aperiodic with no clear light curve shape at the time of observation.

The Kepler light curve of V588 Lyr (Figure 9) shows strong oscillations covering slightly over 1.1 Kepler magnitude of variation with individual maxima and minima levels varying considerably from cycle to cycle. During the time of observation, the maxima and minima had alternate bright and faint cycles. The combination of two periods resulting from a Fourier analysis, P1 (116.39 days) and P2 (217.93 days), permits a fit to the alternating depths, and the autocorrelation analysis agrees with these periods, with even peaks more strongly correlated than the odd peaks. The addition of P3 (198.33 days) slightly improves the result, but a few maxima/minima are not well reproduced. The residuals do not suggest the presence of an additional long-period trend or further short periods, but rather non-sinusoidal variations and additional cycle-to-cycle irregularities. P2 is almost identical to the value given by Dahlmark (2000).

4.4. V1670 Cyg (KID 6127083)

Hoffleit and Sands (1978) classified V1670 Cyg as an SR star with a period of 187.5 days. Dahlmark (2000) rediscovered V1670 Cyg, classifying it as a 191 days Mira with a visual magnitude ranging from 12.4 to 15.0. ASAS found V1670 Cyg to be quasi-periodic, with a period of 193 days and visual amplitude of 1.99 magnitudes.

The light change observed by Kepler (Figure 10) is very regular except for a very bright maximum at the beginning of the time series and a second bright maximum shortly before the end of our time series. There are variations in the depth of the minima from cycle to cycle. Autocorrelation indicates a strong correlation at a period of 187.5 days. Fourier analysis gives a single period of 187.19 days (P1), consistent with the autocorrelation analysis. Subtracting P1 from the light curve reveals a further, rather regular change corresponding to P2 (94.01 days), which is very close to half of P1. No further periodicity was found in the residuals. P1 is in nice agreement with the literature values for the period.

Figure 7. Kepler light curve of EG Lyr. Symbols as in Figure 3. Note that the data span a shorter interval than for most of the other targets.

(Supplemental data of this figure are available in the online journal.)

Figure 8. Kepler light curve of BU Lyr. Symbols as in Figure 3.

(Supplemental data of this figure are available in the online journal.)

Figure 9. Kepler light curve of V588 Lyr. Symbols as in Figure 3.

(Supplemental data of this figure are available in the online journal.)
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The Kepler light curve (Figure 12) shows that the brightnesses of the maxima and minima vary smoothly with time and shows a bump on the ascending branch. The data set is somewhat shorter than the others covering quarters Q6 through Q15. Autocorrelation suggests a strong correlation with a period of 196.5 days. Using Fourier analysis, the times of maxima and minima can be reproduced very well with a single period of 197.15 days (P1). The changing maximum and minimum brightness and the bump can be qualitatively reproduced by adding a long period of 857.39 days (P2) and 99.35 days (P3). P2 is, of course, very poorly defined due to the limited length of the Kepler time series. P1 is not very far off the GCVS value. P3 is approximately half the period length of P1. Its S/N in the Fourier spectrum is only 2.

4.6. V1253 Cyg (KID 8748160)

Dahlmark (2000) found an uncertain period for V1253 Cyg of 188–226 days with a V magnitude range of 11.8 to less than 15 and provided a classification of SR. Pigulski et al. (2009) list the star as quasi-periodic with a period of 187 days.

The Kepler light curve (Figure 12) shows that the brightnesses of the maxima and minima vary smoothly with time and shows a bump on the ascending branch. The data set is somewhat shorter than the others covering quarters Q6 through Q15. Autocorrelation suggests a strong correlation with a period of 196.5 days. Using Fourier analysis, the times of maxima and minima can be reproduced very well with a single period of 197.15 days (P1). The changing maximum and minimum brightness and the bump can be qualitatively reproduced by adding a long period of 857.39 days (P2) and 99.35 days (P3). P2 is, of course, very poorly defined due to the limited length of the Kepler time series. P1 is not very far off the GCVS value. P3 is approximately half the period length of P1. Its S/N in the Fourier spectrum is only 2.

4.7. AF Cyg (KID 9528112)

Fleming & Pickering (1910) noted that the bright (7.4–9.4 mag) M5 star now referred to as AF Cyg was variable. The spectral type at maximum light was confirmed to be M5 III by Keenan (1966). The variability has been extensively studied over the last 100 years. The principal period is ~93 days. Houk (1963) first commented on the LSP of 960 days. Using AAVSO data, Mattei et al. (1997) found periods of 92.9 and 165.9 days. An analysis of four sets of visual observations by Kiss et al. (1999) confirmed the periods of 93 and 163 days and also confirmed an LSP of 921 days. The GCVS lists periods of 92.5, 175.8, and 941.2 days. Andronov & Chinarova (2013) discuss the instabilities observed in the historic light curve. These include the alternating dominance of the 93 and 176 day periods, intervals of regularly strong–weak maxima, and variations in times of the 93 days maximum from 79.4 to 97.4 days. For the data analyzed, they found a dominant 94.2 day period with clusters of other periods present. Hinkle et al. (2002) observed AF Cyg spectroscopically and derived an “orbital” period of 926 ± 36 days, matching the LSP. However, they note that the orbits for all LSP systems look the same, so the motion is likely not orbital in origin. Glass & van Leeuwen (2007) provide a parallax of 4.53±0.64 mas, which allows rough placement on a P–L diagram.

The Kepler light curve of AF Cyg (Figure 13) shows a non-standard alternation of strong and weak maxima that could be interpreted as secondary maxima. The lack of a strict periodicity of this phenomenon suggests that instead this is an interplay of two excited periods of comparable amplitude with a period ratio close to an integer value. Several minor bumps are also present, in particular on the descending part of the light curve. The light curve appears to have a long time variation exceeding the length of our monitoring. The typical amplitude of the light change is 0.5 mag in the Kepmag system.

A Fourier analysis reveals four main periods, and their combination gives a reasonable fit of the Kepler light curve, although some deviations remain. The short-term variability is accounted for by P1 (177.4 days) and P3 (93.6 days). These two periods show a ratio close to 2, and thus agree with the above mentioned suspicion on the origin of the alternating bright and weak maxima. The long time change is represented by a period of 1867 days (P2). While P2 is a strong contributor to the light curve, it is not adequately sampled. A further significant improvement of the fit can be achieved by including a fourth period of 441.3 days. Similar length periods were seen in the test data and may be related to the Kepler year. Autocorrelation analysis contains significant structure,
indicating evidence of multiple periods that are beating against each other. The highest correlation occurs at roughly 186 days, but there are clearly indications of other periods present. Increasing the anti-correlation between 800–1000 days is consistent with the longer period of 1867 days shown in the Fourier analysis.

For AF Cyg, which has been very well studied from the ground, we note the agreement of the two well-sampled Kepler short periods with the literature periods (93 and 176 days) and the disagreement of the poorly sampled Kepler long periods (441 and 1867 days) with the literature period (941 days). The 941 day period is not apparent in the Kepler data. A Fourier analysis on the residual light curve after the removal of P1 through P4 gives an unclear pattern of additional frequencies between 0 and 0.03 c d$^{-1}$ and no significant peaks for frequencies above 0.03 c d$^{-1}$.

4.8. V2412 Cyg (KID 10034169)

The variability of V2412 Cyg was discovered in 2001 as a part of the MISAO Project (Yoshida et al. 2004), but the only additional information was a possible coincidence with NSVS 5651487 (Woźniak et al. 2004a). NSVS 5651487 has a light curve with an ~250 day period. ASAS (Pigulski et al. 2009) lists V2412 Cyg as aperiodic. The GCVS lists a 250 day period for the star and an SR: classification.

The Kepler time series for V2412 Cyg is not continuous (see Figure 14). This star was observed from quarter Q2 through quarter Q6, then again during quarters Q8 and Q9, and finally in quarter Q14. In part, the gaps are due to the placement of V2412 Cyg on the failed Kepler Module 3. The large gaps make it extremely difficult to determine an accurate flux level after each of these gaps. The behavior during the five continuous quarters gives us some clues to the proper treatment of this star. During these quarters, we have strong oscillations covering over 1.5 Kepler magnitudes. The shifts to adjust for discontinuities between these continuous quarters were relatively small. We assume that the corrections in flux for quarters Q8 and Q14 would also be relatively small and we leave them uncorrected.

Times of maxima and minima can be reproduced reasonably well using one period of 255.91 days (P1) only. Variations in the brightness of the maxima and minima can be fitted nicely using a beat period of 241.19 days (P2). A third period of 140.42 days (P3) comes with a somewhat low S/N, but including it helps to reduce the residuals significantly. The light curve shows an asymmetric oscillation with a steeper descent into minima than the rise to maxima, and a slight bump in the ascending side that seems to shift its position from cycle to cycle. Including period P3 partly compensates for these bumps in the rising branches, although some difference remains. Unfortunately, an enticing wiggle in the ascending side during quarter Q14 (JD = 2454833 ≈ 325) is cut off before the star reaches maximum sometime during the missing quarter Q15. P1 and P2 are both close to the GCVS value of 250 days.

4.9. V1953 Cyg (KID 12215566)

Geßner (1988) found that V1953 Cyg had slow semiregular variations with a photographic amplitude of 14.8–15.6 mag and a period of ~150 days. The GCVS classifies V1953 Cyg as an
SRb. The ASAS observations of V1953 Cyg list the star as quasi-periodic with a period of 95.2 days.

Although the Kepler measured light curve for V1953 Cyg (Figure 15) looks quite irregular, with a typical full amplitude of 0.4 mag, a combination of only three periods of 163.07 days (P1), 847.51 days (P2), and 93.41 days (P3) permits a fit to its main shape. P2 is poorly defined. Many details of the light curve, however, cannot be reproduced properly. A Fourier analysis on the residuals gives a number of peaks of similar amplitude between 500 and 50 days. Autocorrelation analysis finds a moderately correlated period of 179.5 days, but the correlation decays rapidly, indicating that no single period dominates the light curve signal. P3 is similar to the ASAS period. P1 may be identical to the 150 day variation seen by Geßner (1988).

5. DISCUSSION

The Kepler data provide a new way to explore AGB pulsation through continuous, high-precision, photometric time series spanning multiple years without significant interruption. Diurnal and seasonal effects in ground-based data result in time series that are too short or too fragmented for proper handling of the complex variability patterns observed in stars with very long periods (e.g., Kerschbaum et al. 2001). We were interested in exploring the various radial modes involved in SR pulsation, looking for LSPs, and searching for the existence of any low amplitude, short-period events or pulsations. For the latter goal, we were especially interested in looking for any periods that might be attributable to non-radial pulsations.

The Kepler data, of course, have limitations. Interruptions of the Kepler time series observations occurred due to telescope rotation every three months. SR variables have periods of the order of months to years (Samus et al. 2012), and extracting periods longer than a Kepler quarter posed special challenges in data reduction. Linking the quarters is surprisingly complicated due to a number of effects that can introduce photometric errors, and we have explored optimum and non-subjective techniques for the construction of light curves spanning the whole Kepler monitoring time span. Another unfortunate reality of Kepler data, impacting this paper as well as the planet search goal of the mission, is that most of the stars observed are moderately faint. As a consequence, most of the variable stars are not among the best studied objects of their classes. In spite of these problems, we find good agreement with the main periods detected in the Kepler data and ground-based results, including the ASAS data set (see Table 3). The differences appear to be astrophysical and we will discuss them below.

5.1. Physical Origins of Pulsation

The physical interpretation of the observed pulsational behavior of red giants has been a topic of research and debate for several decades. Recent results for low luminosity red giants, based also on Kepler data (Bedding et al. 2010; Beck et al. 2011; Hekker et al. 2014), suggest that solar-like oscillations are observed in these stars. For the red giants less luminous than the RGB tip, three parallel P–L sequences are detected (Soszyński et al. 2004) that can be interpreted as radial low overtone modes plus non-radial (l = 1) and (l = 2) p-modes (Takayama et al. 2013). Asteroseismology using SC Kepler data provided the possibility of identifying core helium-burning red giants on the basis of frequency separation of gravity modes (Bedding et al. 2011).

Above the RGB tip, where the classical long-period variables are found, the pulsation behavior is different. In the more luminous stars with their larger light and velocity amplitudes, the role of non-radial modes for the observed (semi-)periodic behavior is expected to be comparably low (e.g., Wood et al. 2004), although some recent results by Stello et al. (2014) may initiate a new discussion on this question. Various observational studies, more recently by Banyai et al. (2013) and Kiss & Bedding (2004), have demonstrated the difference in the variability behavior between RGB stars and the more luminous AGB stars. As pointed out by Xiong & Deng (2007), stability analysis of pulsation modes in red giants shows a change from higher overtone radial modes to low-luminosity red variables to lower overtone radial modes in the more luminous ones. This is in agreement with observations from globular cluster giants (Lebzelter & Wood 2005). Model calculations, in particular of Wood and collaborators (Wood & Olivier 2014, and references therein), find the variability of the more luminous stars dominated by radial modes that are self-excited rather than stochastically excited. Coupling between convection and oscillations has been identified as the most likely excitation mechanism (Xiong & Deng 2007). Buchler et al. (2004) find that irregular pulsations are driven by energy exchange between two nonadiabatic modes in a 2:1 resonance.

Pulsation models nicely reproduce the P–L sequences of luminous red giants (e.g., Soszyński et al. 2007) in terms of a sequence of the fundamental radial mode and several low-order overtone modes. The only exception is sequence D, the LSPs, which we will discuss in more detail below. The observed amplitudes in our program stars place them in the group of luminous red variables. The periods and parallax of AF Cyg demonstrate this unambiguously (Glass & van Leeuwen 2007). Hence, we will focus on radial pulsation modes in this paper. Wood & Olivier (2014) find that strange modes may develop in red giants beside the normal radial modes, but that they are always damped and thus should not be visible beside the normal radial modes on the upper giant branch. However, they might affect the period shown by a radial mode.

5.2. Decomposition of the Light Curve

The Kepler light curves typically appear at first examination to be very complex. However, in all our stars, the combination of two or three periods was sufficient to predict the times of maxima and minima correctly. The exception is BU Lyr, where this is correct for only the second half of the Kepler data set. However, in most cases a single period was not sufficient. This implies, as others have concluded, that even behavior classified as irregular is multiperiodic (Lebzelter & Oebprugger 2009).

For detailed fitting of the complex light change shapes, we used a combination of several periods. The continuity and the high photometric precision lowered the noise level in the Fourier power spectra significantly compared with ground-based surveys. In some cases, the observed changes in amplitudes and period lengths could be traced reasonably well, while in other stars the large residuals remained after subtraction of three to four frequencies, just like in the case of stars well observed from the ground. This is in agreement with other studies that note an irregular component in the light curves (Turner et al. 2010).
The two independent period search methods we applied lead to very similar results for period fits to the light curve. The period detection is robust for up to four periods at the precision and time span of the Kepler data. There are differences between the periods detected in our study and values in the literature based on different data sets for the same star. To explore this further, we downloaded the ASAS data set for one of our stars, V1953 Cyg, from the ASAS website.10

We selected V1953 Cyg because its light curve is one of the most irregular ones in our sample. The fit produced using our Kepler-derived periods can be used to model almost all maxima and minima in the ASAS data set correctly, and the combination of three periods reproduces a remarkable fraction of the changes in amplitude and period length. Naturally, the photometric uncertainties of the ASAS measurements are much larger than those of the Kepler measurements. Therefore, it is not possible to test the quality of the fit of the artificial light curve with similar precision.

In the ASAS database, V1953 Cyg is listed with a period of 95.2 days, although the phased light curve using this period shows considerable scatter. Our Fourier analysis of the same ASAS data gives a period of 95.1 days as the first peak. An analysis of the residuals results in a second period of 66.1 days. The third period is a long period of almost 600 day length. The Kepler data show a third peak at 93.4 days and a second peak at 847.5 days. There is no Fourier peak visible in the ASAS data at the prime 163.1 day Kepler peak. Attempting to fit the Kepler light curve using the three periods derived from the ASAS light curve does not result in a good fit.

We find that the periods derived for semiregular variables are always connected to the star’s behavior at a specific time interval, but are not necessarily transferable to a different data set observed at a different time. To identify the dominant period(s) of an SR variable, an analysis of several pieces of the light curve obtained in different years seems to be necessary.

5.3. Pulsation Mode and Multiple Periods in the Same Mode

Multiple periods in SR variables are known from ground-based data. The Kepler light curves of the SR variables provide extremely clear examples. The multiple periods are manifested in three ways. Most of the program stars have two pulsation modes present that are separated by roughly a factor of two (Table 3). Historical light curves show that the dominant mode can switch between the two excited modes (Buchler et al. 2004). In 30%–50% of stars, a third long period that is ∼9 ± 4 times longer than the dominant period can also be present (Wood et al. 1999). In addition, each of the two pulsation modes can be composed of multiple periods spanning a small range of values (Buchler et al. 2004; Soszyński et al. 2004). The result is that for any given epoch, the resulting light curve can appear irregular or quite periodic. An excellent example is the SRa variable V1766 Cyg, which is described in the literature as fairly regular with a period of 119 days (Huruhata 1983). This is the one star in our program that does not have a second mode present. Nonetheless, during the time of the Kepler observations, the light curve appears to be fairly irregular. This is due to the presence of a number of periods spanning the range from 104 to 122 days. On the other hand, two stars in our sample had SR: or SRb classifications, V1253 Cyg and V2412 Cyg, which imply that, historically, the light curves have been irregular (or badly sampled). These stars do indeed have multiple modes/periods but during the interval of the Kepler observations the light curves were quite regular.

Time variations in the periods of late-type stars pulsating in multiple modes are well known from comparisons of observed and average periods. Changes in the strengths of radial modes also are a feature of type II Cepheids and RV Tauri stars (Pollard et al. 2000). In these stars, as well as in LPVs, variations of this type have been attributed to chaotic processes (Buchler et al. 2004). Using combined sinusoid fits to the LPV light curves from space missions like Kepler or COROT with a limited number of periods will not result in vastly different insight over ground-based analyses of these objects, but does produce more reliable secondary periods. A substantial collection of high-precision data could form the basis for testing statistical models of interior processes in LPVs (see, for example, Buchler et al. 2004).

The ASAS catalog (Pigulski et al. 2009) of variable stars in the Kepler field lists a total of 947 variables. Of these, approximately 43% are in the ASAS category QPER. The QPER category consists mainly of SR variables, many with short periods, although we find that some of our program stars are classified as APER. Miras make up another 6% of the ASAS catalog variables. Figure 16 shows the period distribution of the QPER and Mira classes. A period distribution is the projection of the P–L diagram onto the period axis. We are unable to produce a P–L diagram, since the luminosities of the Kepler field stars are unknown. For most of the program stars, the dominant period is around 200 days, with a shorter period of around 100 days. The longer periods match the long-period SR distribution, which is shared by the Miras. The Miras are fundamental mode pulsators (Soszyński et al. 2013). The figure suggests that for most, if not all, of the program stars the long period is a fundamental mode.

To explore the periodicity patterns detected in our semiregular variables, the period ratios are shown on a Petersen diagram in Figure 17. The Petersen diagram sets the ratio of the longer to the shorter period in relation to the longer period (Petersen 1973). This approach has become widely used for the study of large sets of LPV light curve data (e.g., Wood et al. 1999; Soszyński et al. 2013). In our Figure 17, we see a clustering of data points at period ratios of 1.1 and around 1.8.

10 http://www.astrouw.edu.pl/asas/, January 2014.
The ratios with very long periods have been excluded. We show the theoretical ratios from fundamental mode (P0) and low overtone mode pulsation models (Pn) given in Figure 4 of Wood et al. (1999). The period ratios around 1.8 fall between the theoretical sequences for fundamental to first overtone mode and first to third overtone mode, respectively. All our sample SRVs with the exception of V1766 Cyg are found in that region with a pair of periods. Our result is consistent with the Petersen diagram presented in Wood et al. (1999) for long-period variables in the LMC. In analogy to their results, we conclude that most of the SRVs in our sample are fundamental mode pulsators, which also have the first overtone mode excited.

The period ratios clustering around 1.1, i.e., pairs of periods very close together, are not the result of two different low-order radial pulsation modes (see Soszyński et al., 2013). Soszyński et al. (2004) detected that about 35% of the LMC semiregular variables in the OGLE database show such behavior. In analogy to similar observations found in RR Lyr stars and Cepheids, these authors attribute such periods to non-radial oscillations. However, non-radial oscillations of the size required for M giant SR variability would result in unrealistic distortions (Wood et al., 2004; Nicholls et al., 2009). Non-radial modes also are not expected to provide significant velocity variations (Wood et al., 2004). In the case of AF Cyg, the velocity amplitude is ~5 km s\(^{-1}\). Similar results are found for the related stellar sample presented by Lebzelter & Hinkle (2002).

Bedding et al. (2005), while excluding non-radial oscillations as the origin of multiperiodic behavior, pointed out that the clustering of peaks in the Fourier power spectra of some LPVs has a striking similarity to the power spectra seen for stochastically excited pulsators like our sun. These are peaks from the same pulsation mode but with slightly different periods. However, Buchler et al. (2004) point out that the low mass and high luminosity of AGB stars rules out a stochastic origin and favors chaotic pulsation dynamics arising from nonlinear interaction between two resonant pulsation modes. The light curves show that these peaks can coexist or come and go without changing the overall brightness. Fox & Wood (1982) noted a possible connection to convection. This has been discussed by Buchler et al. (2004), Xiong & Deng (2007), and most recently by Soszyński & Wood (2013). Soszyński & Wood (2013) note that convection carries most of the energy through most of the envelope, but is poorly modeled, resulting in large computational uncertainties.

5.4. Long Secondary Period

As noted in the introduction, the SR variables exhibit LSP variations that have periods longer than the fundamental and typically ~8–10 times longer than the dominant pulsation period (Nicholls et al., 2009). While these long periods have been known for a long time (Houk, 1963, and references therein), LSPs became an astrophysical problem when Wood et al. (1999) identified P–L sequences covering fundamental and overtone radial modes, as well as an LSP sequence, in MACHO observations of LMC AGB stars. Stars with LSPs are multimode pulsators with a low overtone pulsation. In the AGB stars, these are SR variables.

Recent surveys of luminous red giants by Soszyński et al. (2007) and Fraser et al. (2008) show that LSPs are common. Soszyński et al. (2007) suggest that very low amplitude LSPs exist in up to 50% of variable AGB stars. The Kepler mission proved too brief to reliably measure LSPs for any star. However, in agreement with Soszyński et al. (2007), about half of our light curve fits require a long period of a few hundred days length. In the case of V1953 Cyg, an LSP of ~600 days is detectable from ground-based data. We tentatively identify LSPs of 800+ days for this star and 700+ days and 800+ days for V1766 Cyg and V1253 Cyg, respectively. These stars appear indistinguishable from the other SRVs in terms of global parameters like color. Among the SRVs with a long period in our sample, only one (V1766 Cyg) shows in addition a pair of periods of very similar length (104 and 122 days). The other four stars with such pairs of periods do not show an LSP; however, three of them show a third period about half the length of the two similar periods. The third period of BU Lyr is approximately two times larger than its pair of periods.

AF Cyg is well known from ground-based observations to have an LSP (Houk, 1963). In our data, it shows an interesting characteristic of LSPs not previously reported. The ground-based LSP is ~960 days, which is also seen spectroscopically (Hinkle et al., 2002). However, we cannot fit, even by attempting to force a fit by hand, this period to the Kepler data. On the other hand, a period of roughly half the LSP is present. In the few stars where the LSP has been monitored spectroscopically, the LSP is never the dominant photometric signal but is the dominant spectroscopic signal (Hinkle et al., 2002, 2009). Archival photometry of these stars suggests that the LSP can at times be difficult to observe.

The physical cause of LSPs remains unknown (Nicholls et al., 2009). No clear non-radial modes were detected in our data, in agreement with the previous discussion. Other investigators have excluded a number of other causes, with remaining explanations including star spots (Wood et al., 2004) and long-period convective cycles (Stothers, 2010). Long-period convective cycles were mentioned as a possible cause, and discussed above for multiple periods in overtone modes. The requirement of dual-mode pulsation for a long period suggests that the mode-switching mechanism is involved with the long period. Coupling between convection and oscillation in SR pulsation has been invoked by both Buchler et al. (2004) and Xiong & Deng (2007).
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5.5. Very Short-period Variations in LPVs

The 30 minute sample interval of the Kepler observations permits a search for rapid outbursts or very short time variations that have been discussed for LPVs on the basis of Hipparcos data (de Laverny et al. 1998). A detailed search by eye of the program star Kepler light curves for such outbursts lasting from hours to a few days did not result in any detections. The time around the transition between two quarters was excluded. This result adds to other recent studies of this phenomenon that also did not detect such variations (Lebzelter 2011; Woźniak et al. 2004b). We support the conclusion of these works that outbursts of durations less than a day in long-period variables are very rare events.

6. CONCLUSIONS

Kepler data require considerable care in reduction when used for multi-year high-precision photometry. The technical problems have been discussed at length and solutions are presented. The resulting light curves of the SR variables are remarkably featureless at high time resolution and high precision. No variations were detected on “rapid” timescales of one day or shorter. We have undertaken various types of period analysis on the data. While many of the light curves appear irregular, the analysis shows this to be the result of combining two or three regular periods, suggesting that even the most irregular late-type variables are multiperiodic SR variables.

Multiperiodicity is a ubiquitous property of the SR variables that we analyzed. Using a Petersen diagram, we can show the SR variables in the current sample to be fundamental plus first overtone multimode radial pulsators. The multiple periods of the program stars are not solely the result of pulsation in more than one mode. These stars are in fact multiperiodic in three ways. They are generally pulsating in both the fundamental and an overtone mode. They have multiple periods in the dominant pulsation mode. Approximately half of the stars also have a LSP 8–10 times the length of the dominant pulsation period. The strong connection between LSP and multimode overtone pulsation suggests that LSPs are related to the convective processes that drive mode switching and multiperiodic modes in SR variables.

One of our goals was to use Kepler data to compare the different subclasses of SR variables. All the sample stars are multiperiodic with no apparent differences between the SKa, SRb, or SRc subclasses. We interpret the apparent regularity of some light curves as the result of constructive interference between beating periods. The implication, which is not surprising, is that the SR classification scheme is very insensitive to the location of a variable in the P–L diagram. When Gaia data becomes available, it will be possible to place the Milky Way LPVs on the P–L diagram. Mira variables have been separated from the SR variable by pulsation amplitude, but are also single-mode pulsators. Previously, SR variables have been seen as simply low-amplitude versions of the fundamental mode Mira pulsators (Hinkle et al. 1997), but this is clearly an incomplete description. It will be of interest to see how the extensively studied late-type variables fit on a P–L diagram where multimode versus single mode and large-amplitude versus small-amplitude variables can be compared.

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REFERENCES

Andronov, I. L., & Chinarova, L. L. 2013, Czestochowski Kalendark Astronomiczny, ed. B. Woszolek, & A. Kuzmicz, 139
Banyai, E., Kiss, L. L., Bedding, T. R., et al. 2013, MNRAS, 436, 1576
Beck, P. G., Bedding, T. R., Mosser, B., et al. 2011, Sci, 332, 205
Bedding, T. R., Huber, D., Stello, D., et al. 2010, ApJL, 713, L176
Bedding, T. R., Kiss, L. L., Kjeldsen, H., et al. 2005, MNRAS, 361, 1375
Bedding, T. R., Mosser, B., Huber, D., et al. 2011, Natur, 471, 608
Box, G. E. P., & Jenkins, G. M. 1976, Holden-Day Series in Time Series Analysis (Revised ed.; San Francisco: Holden-Day), 21
Bruntt, H., Grundahl, F., Tingley, B., et al. 2003, A&A, 410, 323
Buchler, J. R., Kolláth, Z., & Cadmus, R. R. Jr. 2004, ApJ, 613, 532
Caldwell, D. A., van Cleve, J. E., Jenkins, J. M., et al. 2010, SPIE, 7731, 30
Christensen-Dalsgaard, J., Kjeldsen, H., & Mattei, J. A. 2001, ApJL, 562, L141
Dahlmark, L. 2000, IBVS, 4989, 1
de Laverny, P., Mennessier, M. O., Mignard, F., & Mattei, J. A. 1998, A&A, 330, 169
De Marchi, F., Poretti, E., Montalto, M., et al. 2007, A&A, 471, 515
Fleming, W., & Pickering, E. C. 1910, HartCi, 158, 1
Fox, M. W., & Wood, P. R. 1982, ApJ, 259, 198
Fraser, O. J., Hawley, S. L., & Cook, K. H. 2008, AJ, 136, 1242
Garcia, R. A., Hekker, S., Stello, D., et al. 2011, MNRAS, 414, L6
Gelbner, H. 1988, VSM, 11, 150
Glass, I. S., & van Leeuwen, F. 2007, A&A, 471, 1453
Hekker, S., & Mazumdar, A. 2014, in Proc. IAU Sym 301, ed. J. A. Guzik, W. J. Chaplin, G. Handler, & A. Pigulski (Cambridge: Cambridge Univ. Press), 325
Hinkle, K. H., Fekel, F. C., & Joyce, R. R. 2009, ApJ, 692, 1360
Hinkle, K. H., Lebzelter, T., & Scharlach, W. W. G. 1997, AJ, 114, 2686
Hinkle, K. H., Lebzelter, T., Joyce, R., & Fekel, F. 2002, AJ, 123, 1002
Houk, N. 1963, AJ, 68, 253

The large-amplitude LPV variables are Miras, and these have been proven to be fundamental single-mode variables (Soszyński et al. 2013). Soszyński et al. (2013) also find that most SRVs are double-mode variables with the fundamental mode and first overtone simultaneously excited. Our data similarly show most SRVs pulsating in two modes. As discussed in Soszyński & Wood (2013), AGB stars evolve through instability stages from overtone mode pulsation to fundamental mode pulsation as the luminosity increases. The Miras in the LMC sample investigated by Wood et al. (1999); Soszyński et al. (2013), and others are single-mode variables and do not have an LSP. Since the SR class contains fundamental mode pulsators, the implication is that either LSP behavior limits the amplitude of pulsation or that a large pulsation amplitude somehow excludes LSPs. Both explanations require that LSPs are an intrinsic feature of an AGB star related to overtone pulsation. This agrees with the conclusion reached by Wood & Nicholls (2009) using other lines of evidence.

One of our goals was to use Kepler data to compare the different subclasses of SR variables. All the sample stars are multiperiodic with no apparent differences between the SKa, SRb, or SRc subclasses. We interpret the apparent regularity of some light curves as the result of constructive interference between beating periods. The implication, which is not surprising, is that the SR classification scheme is very insensitive to the location of a variable in the P–L diagram. When Gaia data becomes available, it will be possible to place the Milky Way LPVs on the P–L diagram. Mira variables have been separated from the SR variable by pulsation amplitude, but are also single-mode pulsators. Previously, SR variables have been seen as simply low-amplitude versions of the fundamental mode Mira pulsators (Hinkle et al. 1997), but this is clearly an incomplete description. It will be of interest to see how the extensively studied late-type variables fit on a P–L diagram where multimode versus single mode and large-amplitude versus small-amplitude variables can be compared.
