Kepler Observations of Three SRS: Stars—V616 Lyrae, V607 Lyrae, and V621 Lyrae

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Abstract Kepler data for three SRS: stars, V616 Lyrae, V607 Lyrae, and V621 Lyrae, were analyzed to study their period structure. Two of the stars had confirmed SRS light curve characteristics. V616 Lyr shows two strong periods at 16.91 days and 8.18 days. V607 Lyr shows one strong period at 13.55 days. V616 Lyr and V607 Lyr also display amplitude changes common to the SR stars. Variability was not detected for V621 Lyr. Evidence for solar-like oscillations in V616 Lyr is presented.

1. Introduction

Semiregular, or SR, stars are a class of pulsating variable for giant and supergiant stars with intermediate to late spectral types and periods of tens to thousands of days. The *General Catalogue of Variable Stars* (GCVS) variability type descriptions explain the "semiregular" nature of these stars by referring to "noticeable periodicity in their light changes, accompanied or sometimes interrupted by various irregularities" (Samus *et al.* 2017). Traditionally the classification was divided into four subgroups (SRa, SRb, SRc, and SRd) depending on the level of periodicity, amplitudes, and/or spectral types.

The "76th Name-List of Variable Stars" introduced a new subgroup of the SR variability type—SRS stars—which are "Semiregular pulsating red giants with short periods (several days to a month), probably high-overtone pulsators." and AU Ari was named as the prototype for this category (Kazarovets *et al.* 2001). As of May 2018, the AAVSO International Variable Star Index (VSX) listed 375 stars classified as SRS stars and another 19 uncertain SRS: designations (Watson *et al.* 2017). The era of large surveys has dramatically increased the number of stars in the VSX database with 73,917 SRS stars and another 36,510 SRS: candidates as of July 2020, with most of the new ones detected by OGLE and ASASSN-V missions.

Studies of the SR stars are complicated by both the multiperiodic structure common to many SR stars (Kiss *et al.* 1999; Fuentes-Morales and Vogt 2014) and amplitude changes common in pulsating red giants (Percy and Laing 2017). As pointed out by Koen *et al.* (2002), these complications mean that "long, uninterrupted time series of observations are required to make reliable deductions." Cadmus (2015) summarized efforts in the long term monitoring of SR stars and called for additional observations and analysis of this stellar type. The Kepler Mission provided an opportunity to study variable stars with high precision and long temporal baselines. The recent review paper by Molnár *et al.* (2016) details some successes in variable star research using Kepler data. Hartig *et al.* (2014) presented results for long-period SR stars in the Kepler field and was able to study the multiperiodic nature common to many SR stars. While the entire category of SR stars shows a range of behaviors, the SRS stars form the short-period, small-amplitude extreme end. As such the careful analysis of members of this class can eventually provide additional insight into the underlying physical processes at work.

Several SRS: stars are included in the field of view of the original Kepler mission. These are stars which have not been well observed prior to Kepler; see section 2.2 for additional details. The high precision, closely spaced, and long baseline observations by Kepler have the potential to provide a much clearer view of the variable nature of these stars. While they were included as "test cases" for the analysis in the Hartig *et al.* (2014) work, the authors pointed out that additional analysis would be needed to carefully determine the period structure for these three stars. This paper presents that analysis.

2. Observations

2.1. Target stars

The three SRS: stars presented in this study are in the region of the open cluster NGC 6791 and were originally identified as variables by Bruntt *et al.* (2003). Table 1 lists the three stars along with their cross identification numbers and current period values from the GCVS.

Table 1. Target stars.

Kepler Ident.	*GCVS Name*	*NGC 6791 Ident.*	*Max.*	*GCVS Period (days)*
2437359	V616 Lyr	V73	14.84	20.9
2569737	V607 Lyr	V97	16.49	9.563
2570059	V621 Lyr	V99	17.54	10:

2.2. Previous ground-based photometric observations

After being identified as variables by Bruntt *et al.* (2003), additional ground based observations have been quite limited. V616 Lyr had subsequent observations by Mochejska *et al.* (2003) which indicated an irregular variability with an estimated period of 34 days. Mochejska *et al.* (2005) determined a period of 13.6206 days for V607 Lyr, but did not list any period for V621 Lyr. One additional study of V621 Lyr (de Marchi *et al.* 2007) was also not able to confirm any variability for this star.

There are minimal observations in the AAVSO database for these stars with a total of 32 observations for V616 Lyr, 4 observations for V607 Lyr, and 5 observations for V621 Lyr. In all three cases the observations are spaced far enough apart that they are insufficient to perform any period analysis.

2.3. Spectroscopic observations

Our earlier work (Hartig *et al.* 2014) included spectroscopic classification of all three stars. We classified V616 Lyr as G9 III based on our spectra taken in 2011 May with the four-meter Mayall telescope at Kitt Peak National Observatory. This agrees favorably with the classification of K0 III-IV from Kinman (1965) based on photographic plates. V607 Lyr and V621 Lyr were too faint on the dates of our observations to acquire spectra. Instead, Hartig *et al.* (2014) used V–K colors from the Naval Observatory Merged Astrometric Dataset (NOMAD) and found V607 Lyr to be a K0 and V621 Lyr a G8. They also stated that these three stars are likely on the red giant branch (RGB).

A search of a number of databases turned up no useful additional spectral data for these stars. We searched ASAS, ASAS-SN, APOGEE, LAMOST, and articles in the literature. The Kepler Index Catalog (KIC) does give T_{eff} for our stars based on SDSS colors and model atmospheres (Brown *et al.* 2011) and they generally agree with our results in Table 2 within the margin of error noted in Brown *et al.*

With the classifications given in Hartig *et al.* (2014), including their likely location on the RGB, along with the calibration of MK spectral types from Drilling and Landolt (2000), we determined the T_{eff} and calculated log $(L/L_{\odot})$ as shown in Table 2. The values in Table 2 will be used later in the Conclusions section.

2.4. Kepler observations

The Kepler Space Telescope collected long cadence data for these stars for various quarters over the lifetime of the original mission. V616 Lyr is the brightest of the three stars and was observed as a target object during all 17 quarters of the original Kepler mission. V607 Lyr was observed as a target object for quarters 2–10 and 13–17, while V621 Lyr, the faintest of our stars, was observed as a target object only for quarters 6–9 and 14–17. Both target pixel files and processed light curve files for these observations can be downloaded from the on-line MAST archive.

While the missing quarters for these stars would normally be unrecoverable, our stars lie within an open cluster which was an area of interest for the Kepler mission and observed as a series of 20 × 100 pixel custom apertures covering the region during the entire mission. This allows the possibility of extracting the target stars during quarters where the individual target was not observed or where the default aperture was too small to capture the entire flux. In the analysis sections for each star we indicate the specific KID numbers for the custom aperture used to extract or re-extract data we used. Figure 1 shows the locations of the three target stars in the cluster on one section of a Kepler Full Frame Image (FFI).

Table 2. Spectroscopic quantities.

GCVS Name	*Spectral Type*[a]	*T_{eff} (K) (This study)*	*log $(L/L_{\odot})$ (This study)*
V616 Lyr	G9 III	4730	1.78
V607 Lyr	K0	4660	1.82
V621 Lyr	G8	4800	1.74

[a] *From Hartig* et al. *2014.*

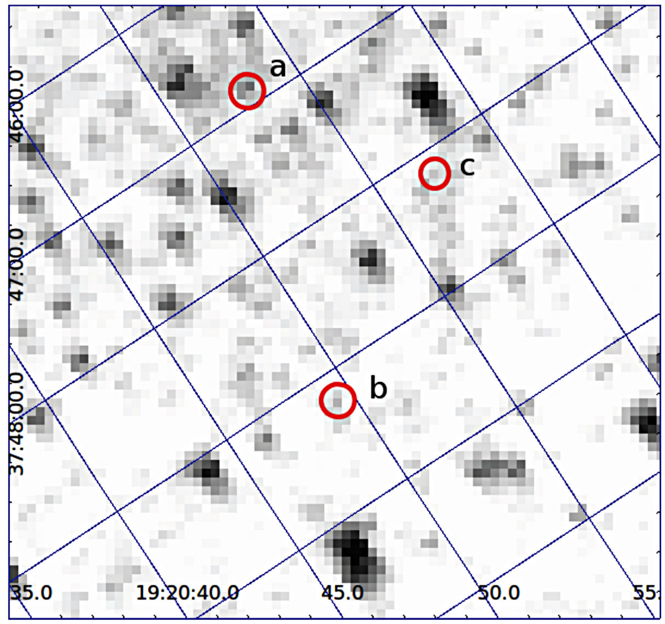

Figure 1. A section of the Kepler FFI for the region of the open cluster NGC 6791 including our three target stars, a) V616 Lyr, b) V607 Lyr, c) V621 Lyr.

3. Analysis and results

3.1. General Kepler analysis

Each target for the Kepler mission defines a default aperture to be used for the standard aperture photometry (SAP) surrounded by a larger target aperture of data which is saved in a target pixel file. For each of our stars, we examined the light curves produced by the default aperture as well as slightly larger or smaller apertures selected from the target pixel file. In particular, we looked for indications that the default aperture might not include enough of the variable star's flux at maximum or that too much scattered flux from a neighboring star might be included for a particular star. The details of this analysis are given for each star in the sections below.

The Kepler mission observations also include several instrumental effects that must be properly dealt with in the data analysis stage. Some of these effects are described in more detail in papers by Hartig *et al.* (2014) and Molnar *et al.* (2016) as well as the *Kepler Data Processing Handbook* (Smith *et al.* 2017). For quarters in which we extracted the light curves from the target pixel files, these instrumental effects needed to be removed via co-trending, using the PyKE software function kepcotrend (Still and Barclay 2012). To maintain consistency in the analysis between quarters, the co-trending was performed on the standard aperture photometry (SAP) light curves for all quarters regardless of whether they came from the default target apertures or were re-extracted from target pixel files.

Following co-trending, the light curve sections for each quarter were cleaned to remove null values and problematic quality-flagged data points. The individual quarters were then shifted to a common mean flux level to form a long-baseline light curve. These full light curves were examined visually, and period analysis was done using a Lomb-Scargle algorithm. The dominant periods found by the Lomb-Scargle analysis were further tested using both phase folding and curve fitting.

3.2. V616 Lyr

The Kepler mission included V616 Lyr as a target for quarters Q01 though Q17, meaning that target pixel files and light curve files were available from the archive for the entire mission. We examined the target pixel files to determine if the default aperture sufficiently captures the flux from the star. Of our three stars, V616 Lyr is the brightest without very close neighboring stars, and examination of alternate aperture choices did not show any problems with the default aperture. Once this was determined, the instrumental effects were removed using the steps outlined in section 3.1 above.

The light curve for V616 Lyr shows the typical SR "noticeable periodicity" with the changing curve shape typical of multiperiodic signals. Figure 2 shows a section of the light curve where these changes are particularly evident.

The Lomb-Scargle periodogram for V616 Lyr indicates two dominant periods in the light curve as shown in Figure 3. The dominant period peak is found at 16.91 days with an additional strong peak at a period of 8.18 days. The dominant peak at 16.91 days is surrounded by other side peaks and the structure as seen in Figure 3b may indicate the presence of an additional weaker signal at a period in the range between 15 and 16 days.

The splitting of the periodogram in the regions of the two dominant periods is often seen in stochastically excited oscillators (Bedding *et al.* 2005). Following the method of Bedding, we have fit the periodogram in the regions near these dominant frequencies with Lorentzian profiles. The resulting fits are shown in Figure 4. For the strongest peak, Figure 4a, the Lorentzian gives a central frequency of 0.0598 d^{-1} and a full width half max of 0.0039 d^{-1}, which translate to a period of 16.7 days and a mode lifetime of 82 days. It is noted that the asymmetry in the structure of the periodogram results in a Lorentzian peak that is offset slightly toward lower periods compared to the peak period. For the secondary peak, Figure 4b, the Lorentzian profile gives a central frequency of 0.122 d^{-1} and a full width half max of 0.0031 d^{-1}, which translate to a period of 8.2 days and a mode lifetime of 103 days.

Curve fitting shows that many of the features in the light curve for V616 Lyr are reproduced with a two-period fit using the two dominant periods of 16.91 days and 8.18 days. Figure 5 shows two sections of the light curve where the fit to the light curve is more and less successful in matching the data. In general, the maxima and minima of the light curve are sharper than a pure sinusoidal curve of the fitting model, which caused the curve fit to have a lower amplitude than the data, but we also see that there are amplitude changes in the light curve which are not matched well with the two-period fit. After trying three period fits with the dominant periods of 16.91 and 8.18 along with a third period in the range of 14.5 to 16.5 days, we find that a period of 15.3 days shows some improvement, but not enough to justify confidence that the third period has any astrophysical significance. As such, we use the two dominant periods in our conclusions.

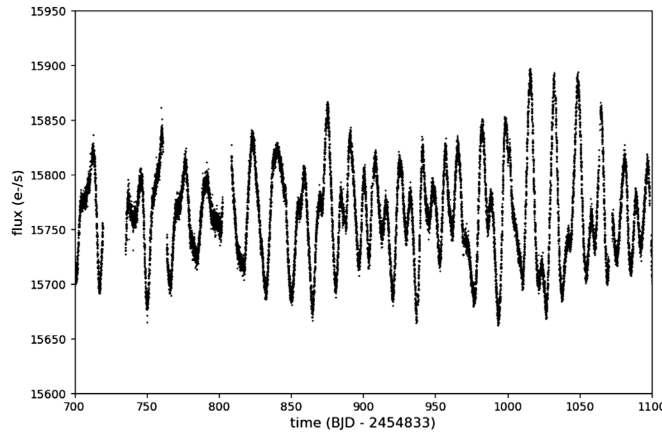

Figure 2. A section of the composite Kepler light curve for V616 Lyr showing the typical SR star "noticeable periodicity" but also indications of mutli-periodicity as the curve shape changes over the span.

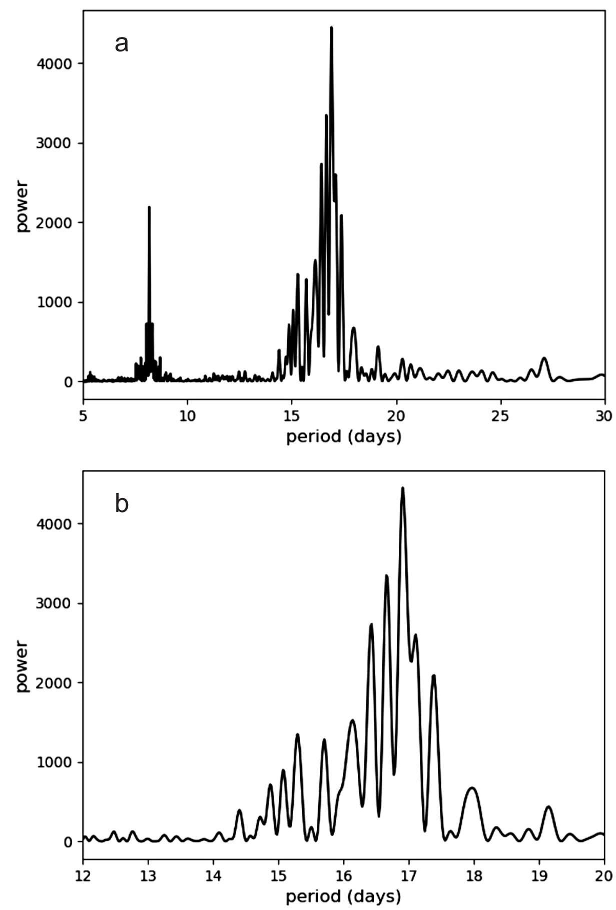

Figure 3. The Lomb-Scargle periodogram for V616 Lyr: a) the range from 5 days to 30 days showing the two dominant periods found in the light curve, b) a close up of the region from 12 days to 20 days showing the structure surrounding the dominant period.

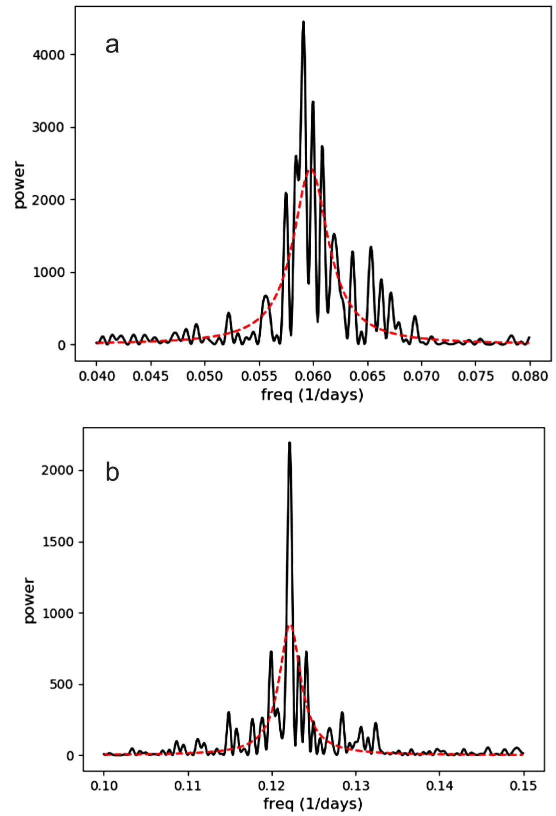

Figure 4. The Lomb-Scargle periodogram in units of frequency for V616 Lyr, with the Lorentzian fits to the two main peaks: a) the dominant peak at a period of 16.7 days and b) the secondary peak at a period of 8.2 days.

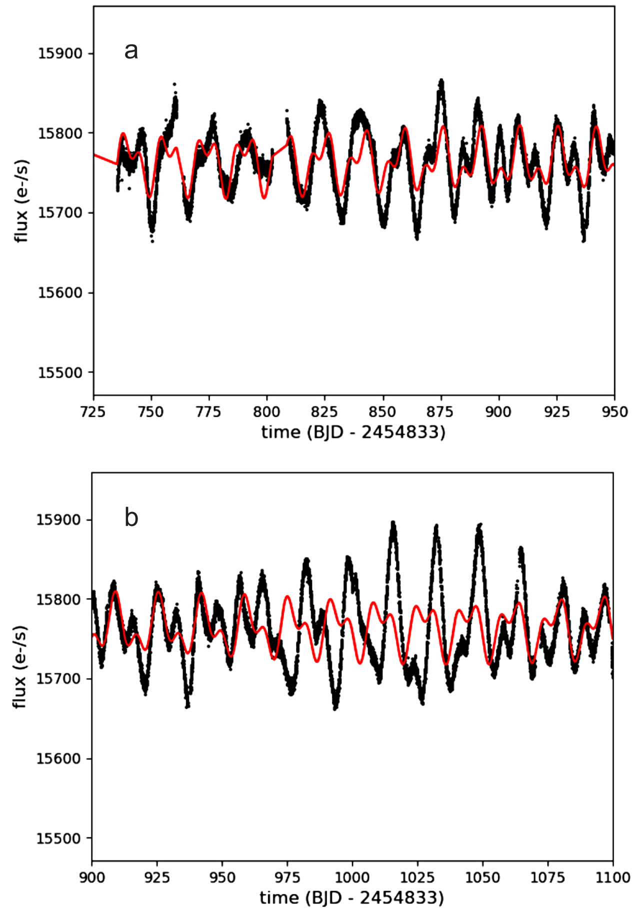

Figure 5. Sections of the V616 Lyr light curve with the data points shown as black dots and a model fit using 16.91 days and 8.18 days as a red line. a) shows a section where the model fit is good, while b) shows a section where the model fit is significantly weaker.

3.3. V607 Lyr

For V607 Lyr, the Kepler mission observed the star for 14 of the 17 quarters. To get a full light curve spanning the entire mission, we needed to extract data for quarters 1, 11, and 12 from the open cluster custom apertures. The star fell on Kepler ID 100000929 for quarter 1, and KID 100000928 was used for quarters 11 and 12.

Since V607 Lyr is a fainter star, the default aperture used by the Kepler pipeline was smaller than that used for V616 Lyr. In some quarters, the default aperture used was only two pixels. By examining these default apertures and comparing the light curves created from larger apertures, we determined that the default aperture missed flux at the maxima of the star's oscillation. We constructed new apertures that better captured the variability. The extracted light curves using these new apertures were co-trended and shifted as described in the general analysis section 3.1 above.

Visual inspection of the full light curve shows the strong periodicity with some variation to the curve shape and amplitude as seen in Figure 6. The oscillations are much more regular for V607 Lyr compared to those for V616 Lyr.

Period analysis for V607 Lyr, as shown in the periodogram in Figure 7, indicates several periods. There is a strong peak at a period of 13.55 days which dominates the light curve, but there is also a pair of lower power peaks at periods of 14.48 and 14.68 days. Curve fitting with a single period of 13.55 days provides a reasonable fit for the timing of the light curve as shown in Figure 8 but not the amplitudes, due to the fact

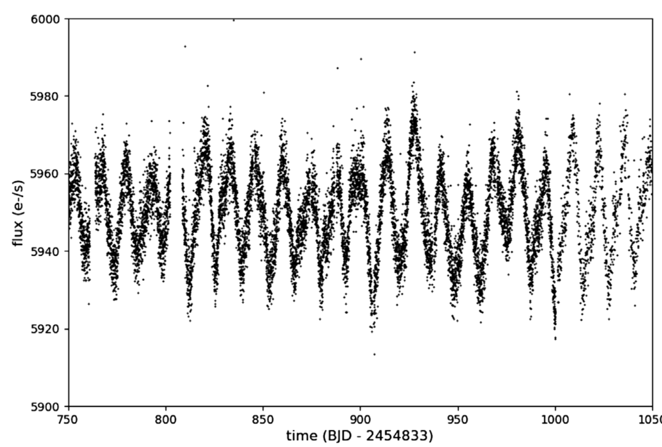

Figure 6. Section of the V607 Lyr light curve showing strong periodicity accompanied by some variation in curve shape and height.

that the maxima and minima are steeper than a pure sinusoidal variation as well as to the variable amplitudes over the full span. Adding in one or two additional periods in the range of 14.48–14.68 days creates beat periods in the curve fitting which better approximate the changing amplitudes, but these periods may not represent pulsation periods but some other mechanism of amplitude change. Since this periodogram is significantly

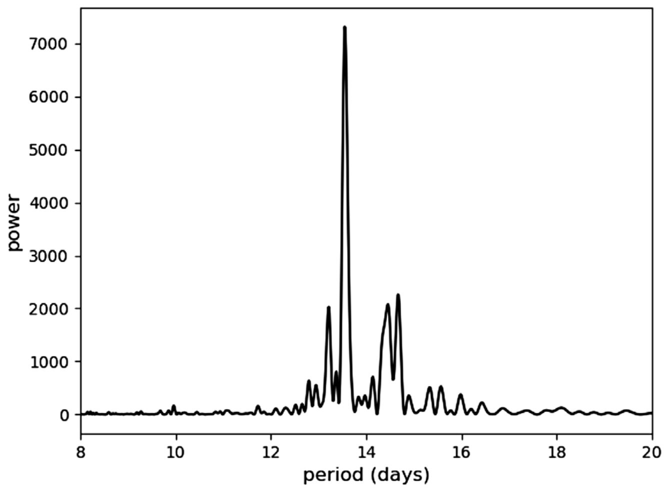

Figure 7. The Lomb-Scargle periodogram for V607 Lyr showing the dominant periods found in the light curve.

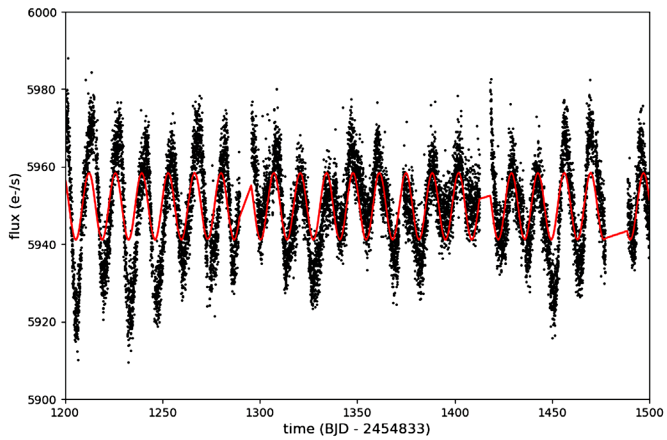

Figure 8. The V607 Lyr light curve data shown as black dots with a solid red line showing the curve fit using the 13.55-day period.

narrower without the characteristic splitting seen for V616 Lyr, we did not fit this peak with a Lorentzian profile.

3.4. V621 Lyr

The original Kepler mission included V621 Lyr as a specific target for only eight quarters. V621 Lyr is found on the KID 100000930 custom aperture for the missing quarters. The default apertures for this star are not consistent between the different quarters and vary from six pixels down to a single pixel. Complicating the analysis is the fact that V621 Lyr is faint, with a nearby brighter star identified only as TGM2014 15004 in Simbad.

Figure 9a shows the region of our star from a Kepler Full Frame Image (FFI) in the middle of quarter 6. Figure 9b shows the region of these stars from the DSS image (rotated to align with the Kepler FFI) with V621 Lyr marked with cross-hairs using the Aladin viewer. From these images it is clear that Kepler is barely resolving V621 Lyr and any aperture for the star will contain flux from the nearby brighter star TGM2014 15004 located below and to the left of V621 Lyr.

After trying several possible apertures, we selected a two-pixel aperture that included the pixel with the target coordinates

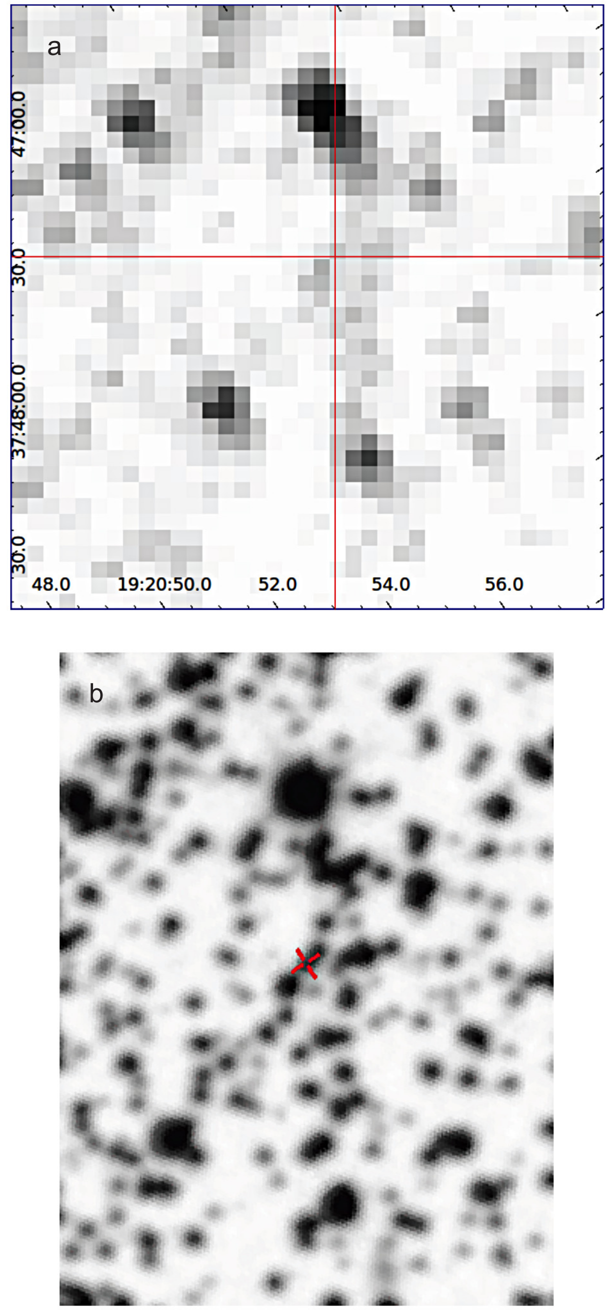

Figure 9. a) Kepler FFI image for the region around V621 Lyr which is marked with a red cross-hair; b) DSS image for the region around V621 Lyr which is marked with a red cross-hair.

for V621 Lyr as well as a second pixel geometrically closest to the target coordinates. For comparison, we also extracted a light curve for the neighboring brighter star using a similar procedure. To remove the instrumental effects, we co-trended using the first five co-trending basis vectors. For quarters 2 and 12, significant instrumental artifacts remained in the light curves for both our target star and the neighboring bright star and these quarters were excluded from our full light curve.

Visual examination of the light curve for V621 Lyr as shown in Figure 10 indicates that we do not have the kind of clear variation seen in V616 Lyr or V607 Lyr. The light curve is dominated by scatter on the order of 0.25% of the flux.

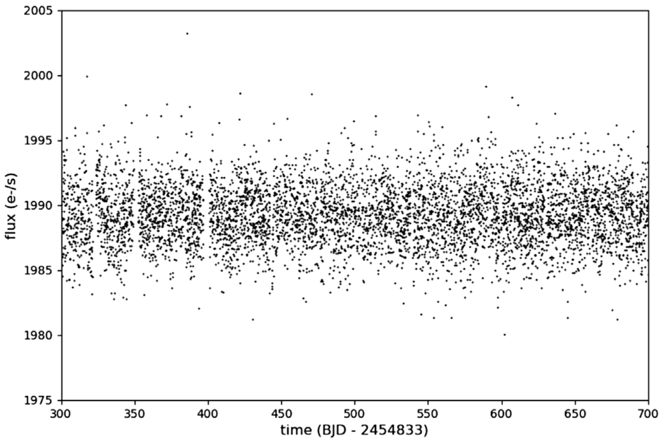

Figure 10. A section of the light curve for V621 Lyr showing little obvious variability.

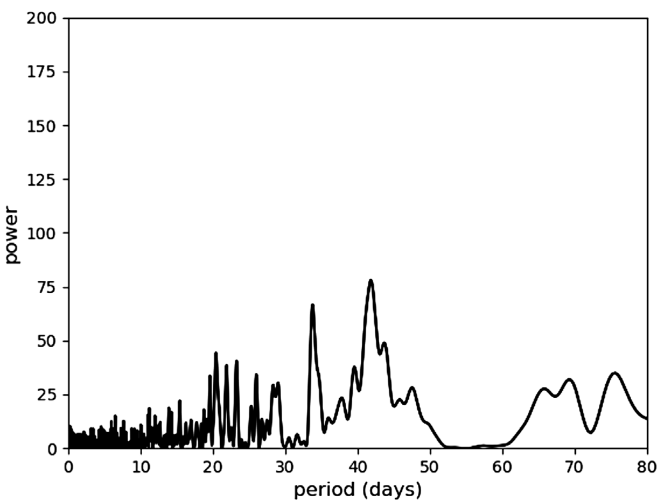

Figure 11. The Lomb-Scargle periodogram for V621 Lyr for the range of 2 days to 80 days.

Running period analysis on this light curve using a Lomb-Scargle periodogram, as seen in Figure 11, results in only low power signals. Analysis of the neighboring brighter star shows a similar pattern of low power signals in this period range indicating that the signals may be remaining instrumental effects and not indicative of astrophysical variability in our target star.

4. Conclusions

4.1. V616 Lyr

Our analysis of V616 Lyr supports its classification as an SRS type variable. It has a dominant period of less than 20 days with amplitude changes typical of the semiregular stars. V616 Lyr is clearly multiperiodic, showing two dominant periods. There may be additional weaker periods which may be related to the changing amplitudes, but we caution against a strict interpretation that these are true pulsation periods. Percy and Laing (2017) point out that these amplitude variations remain unexplained.

Using the interpretation of Bedding *et al.* (2005), V616 Lyr shows strong indications of stochastically excited oscillations with a mode lifetime of approximately 82 and 103 days for the dominant and secondary periods, respectively (corresponding to 5 and 12.6 pulsational cycles). The analysis on L2 Pup in Bedding *et al.* (2005) found a similar relationship of a mode lifetime of 12.5 pulsation cycles. Bedding *et al.* (2010) also concluded that red giants can have mode lifetimes greater than 10 days such as those we find for V616 Lyr.

Table 3. Periods detected in Kepler data.

Source	*V616 Lyr periods (days)*	*V607 Lyr periods (days)*
This work	16.91 and 8.18	13.55
Neilsen *et al.* (2013)	16.68	14.733
Reinhold *et al.* (2013)	17.45, 14.24	
McQuillan *et al.* (2014)	16.415	13.767
Hartig *et al.* (2014)	370.11, 189.10, 16.5	371.31, 189.10, 13.54

As V616 Lyr is a bimodal pulsating red giant, we can compare the two dominant periods similar to the work of Percy (2020). In the case of V616 Lyr, the dominant longer period (Pa) and shorter period (Pb) have a log (Pa) value of 1.23 and a value of 0.48 for the ratio of the periods (Pb / Pa). These values place V616 Lyr in the lower left grouping of stars in the Peterson diagram shown as Figure 1 of Percy 2020. These shorter period stars with period ratios around 0.5 were interpreted as ones oscillating in the first and third overtone modes or possibly the fundamental and first overtone modes.

As pointed out by Koen *et al.* (2002), the combination of these stars' multiperiodicity along with the semiregular nature of the SRS stars results in changing the curve shape over time, which can be difficult to analyze. This helps to explain how other observers could find very different periods when examining these stars for short time spans with ground-based data.

The Kepler observations for V616 Lyr were also analyzed by other research groups but with some important differences in analysis which have the potential to influence their results. The results from Neilsen *et al.* (2013) and McQuillan *et al.* (2014) used an automated analysis to determine “rotational” periods using the standard PDC light curves. In these papers, they looked only for a single period and did not look for the expected multiperiodicity often found in SRS stars. Reinhold *et al.* (2013) used only a single quarter of Kepler data. Hartig *et al.* (2014) used custom apertures but did not fully remove the instrumental effects from those light curves. Table 3 shows a comparison of the results of this work with these other sources for both V616 Lyr and V607 Lyr discussed in the next section.

4.2. V607 Lyr

Our analysis of V607 Lyr also supports its classification as an SRS type variable. It has a dominant period less than 20 days with amplitude changes typical of the semiregular stars. Again we have identified additional weaker periods which may be related to the changing amplitudes or stochastic nature of the oscillations.

Unlike V616 Lyr, V607 Lyr is dominated by only one oscillation period. While the bimodal pulsators are common in the red giants, single dominating periods are also found. Without the bimodal periods, it is harder to interpret which pulsation mode is active in V607 Lyr. The much narrower peak for V607 Lyr also indicates that whatever mode of oscillation is in action, it is significantly more stable than the oscillations in V616 Lyr.

As discussed for V616 Lyr, there are variations between the analysis of the Kepler data on V607 Lyr done by different authors as seen in Table 3 in the previous section. In the case of V607 Lyr, the periods found have somewhat more consistency due to the more stable nature of the star. Again we argue that the more careful analysis done in this paper using custom apertures as opposed to the standard PDC light curves is more likely to yield a reliable period estimate.

4.3. V621 Lyr

Our analysis of V621 Lyr was not able to confirm variability in this faint star. Kepler observations have high frequency resolution but are not highly resolved spatially. The crowded field around V621 Lyr complicates the analysis enough that we cannot claim that V621 Lyr is not a variable, but we clearly do not detect any strong variability in the region including V621 Lyr and the neighboring stars during the four years of the Kepler mission.

4.4. Solar-like oscillations

The question of solar-like oscillations (stochastically excited and damped) in red giants has been the subject of discussion for some time with results supporting detections from the ground and space including Merline (1999), Stello *et al.* (2007), Hekker *et al.* (2010), and numerous others. Using the higher signal-to-noise data from Kepler, Bedding *et al.* (2010) found unambiguous evidence of solar-like oscillations in red giants. Bedding *et al.* (2005) found solar-like oscillations in the SR M star L2 Puppis while Mosser *et al.* (2013 and references therein) used ground-based and Kepler data to demonstrate that solar-like oscillations are found in SR variables over a wide range of spectral types.

Aerts *et al.* (2010) discuss the location of pulsating red giants on the HR Diagram, specifically those that have been shown to have solar-like oscillations. Their Figure 2.2 plots log $(L/L_{\odot})$ vs log T_{eff} using results from an earlier work by Carrier and Eggenberger (2006). The values from Table 2 of our paper place V616 Lyr and V 607 Lyr into Figure 2.2 from Aerts *et al.* at positions very close to the G9.5 IIIb star ε Oph, a pulsating red giant. This does not prove that the oscillations in V616 Lyr and V 607 Lyr are solar-like; however we note they do occupy a part of the pulsation HR diagram where similar G and K stars with confirmed solar-like oscillations are found. In particular as noted above for V616 Lyr, the evidence of solar-like oscillations is strongly supported by splitting of the periodogram in the regions of the two dominant periods. The spectroscopic results further support that in the case of V616 Lyr. No such splitting of the periodogram occurred for V607 Lyr so the evidence of solar-type oscillations is less convincing. We draw no conclusion about solar-like oscillations in V621 Lyr since were unable to detect any variation in its light curve.

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