VARYING VARIABLES: CHANGES IN RR LYRAE IN *TESS* DATA

1 Introduction

There are a number of different types of variable sources in the sky. In this research we are looking at properties of one particular type of star that varies in brightness - RR Lyrae stars. These variable stars radially pulsate, change in physical size up to half their radius, and vary in brightness up to approximately one magnitude with periods of about half a day.

There are three different types of RR Lyrae variables: RRab, RRc, and RRd. RRab and RRc types oscillate in the fundamental and first overtone modes, respectively. RRd types oscillate in both the fundamental and first overtone modes simultaneously.

The data we will be looking at comes from the Transiting Exoplanet Survey Satellite (*TESS*). This is a space telescope with a primary mission of detecting planets around other stars. In the primary mission, *TESS* imaged the same portion of the sky for about one month, then moved on to an adjacent portion of the sky. In its first year it surveyed the entire sky south of the ecliptic, and in its second it surveyed the sky north of the ecliptic. It is currently on its third year and is reimaging the southern sky again.

TESS takes images at different intervals. In the primary mission it acquired two sets of data - short cadence observations (two minutes) of a certain number of pre-selected targets, and longer cadence observations (about 30 minutes) of every target in view of the cameras. Because the cadence of images is much less than the pulsation period, and because *TESS* is able to continuously monitor the sky, it makes it an excellent dataset to study RR Lyrae variables.

Figure 1 is a screenshot of the GUI. In the following will be a discussion about how to classify an RR Lyrae, and look for interesting features of its pulsation, using this GUI.

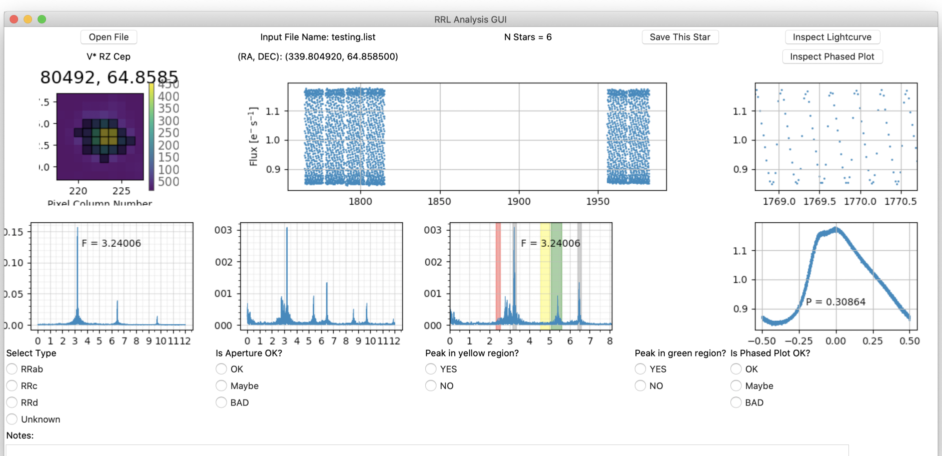

Figure 1: A screenshot of the GUI used to visualize and analyze TESS data of RR Lyrae variables.

2 Checking The Images

The first check that must be done is to verify that we are looking at data for the correct star and there are no nearby bright objects that could affect the results.

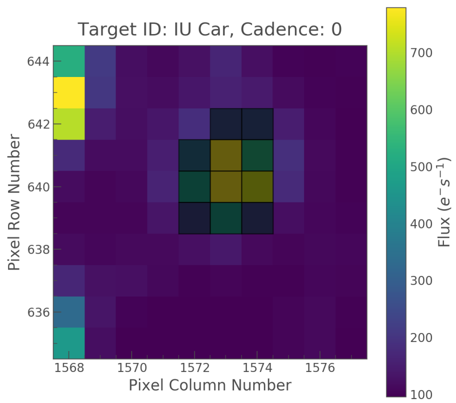

Figure 2: An example of an isolated target star with a well-defined aperture.

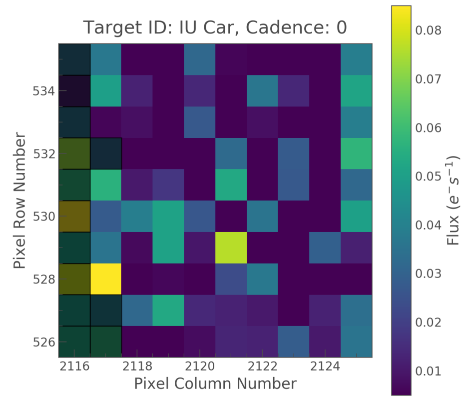

Figure 3: An example of a bad image with an aperture that does not clearly cover a well-defined central object.

TESS has large pixels, so the images it takes do not look like "normal" images that one is accustomed to seeing from telescopes or in textbooks. Each pixel in a *TESS* image covers 21 arcseconds on the sky. As a comparison, the seeing (essentially the best possible resolution you can get) for good observing sites on the Earth is around 1 arcsecond. The benefits and drawbacks of different sized pixels is not important, but one must realize that we will not be looking at Hubble-quality images, even though the data collected by *TESS* exceeds Hubble in certain ways. Much more detail about *TESS* and its imaging system can be found here.

An example image for the star being analyzed is shown in the upper left of the GUI that has the defined aperture overlayed as a grayed area. Figures 2 and 3 show an example of both a good and bad aperture definition, respectively. The "good" aperture definition has a brighter region near the center of the image, with the darker overlayed aperture covering the brightest pixels, and a smooth background with no contamination from any nearby objects. The "bad" aperture definition has a number of bright pixels spread across the image with the aperture defined primarily as the leftmost column in the image.

This is not strictly true, but for the most part, the target RR Lyrae star *should* be in the center of the image and those pixels *should* show a clear signal. It is possible there are other objects (bright pixels) in the image, and this is fine as long as the aperture does not encompass pixels that obviously belong to another source.

If the image and/or aperture are clearly bad/wrong, mark this option in the GUI, and if there could be possible contamination from other sources, or if you are unsure about the quality of the aperture, mark "Maybe".

3 Typing RR Lyrae

The characteristics of the different types of RR Lyrae can easily be seen in *TESS* data. In this section we will see what defines the lightcurves of each type, and what data from *TESS* looks like for these stars.

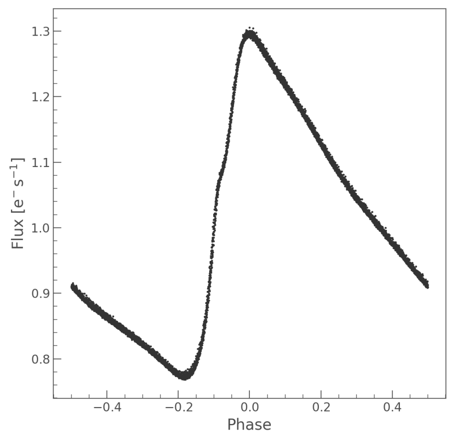

Figure 4: The phased lightcurve for an RRab star from *TESS* data.

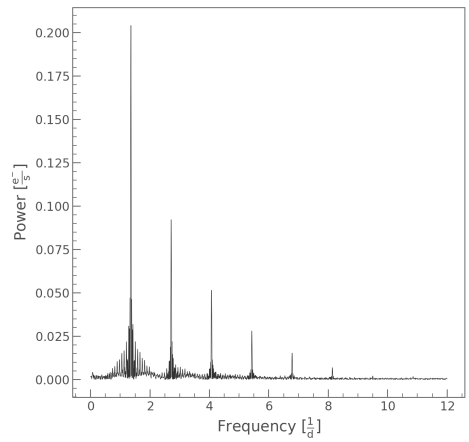

Figure 5: Lomb-Scargle analysis of the RRab star shown in Figure 4.

3.1 RRab

In Figure 4 is the phased (folded) lightcurve of an RRab type. It should be noted that the x-axis of this plot goes from -0.5 to +0.5 in phase, with 0.0 (max light) being at the center. One can see a few defining features of the changing brightness of this star.

First, there is a rapid rise in brightness at a phase of just before ~ 0.0. In typical RRab types, this brightening portion is $\sim 10 - 15\%$ of the pulsation period. After maximum brightness, the lightcurve slowly decreases (becomes dimmer) over the rest of the pulsation period. Occassionally there are "bumps" or "humps" in the lightcurve during the falling portion (usually just before the rapid rise).

In Figure 5 is the results of a Lomb-Scargle analysis of the periodicity of the signal for this star from *TESS* data. The details of how this analysis works are not important, but interpreting what the graph says and means is.

One will notice there are peaks with decreasing height moving toward the right. The highest peak in the plot (at $\sim 1.4\ d^{-1}$) is the primary pulsation frequency of this star. The decreasing peaks are harmonics of this peak (nf where $n = 1, 2, 3, etc$). There are smaller side-peaks near the main peaks, which are more or less symmetric and much lower in amplitude. Other than the main peak and its harmonics, there are no other notable features in this plot.

3.2 RRc

The phased lightcurve of an RRc type is shown in Figure 6. One can see that the changing brightness for this star follows an almost sinusoidal shape. There is no rapid rise in the brightness like an RRab, this star brightens and dims at roughly the same rate.

There is a small "hump" in the lightcurve just before max light. These humps can be more or less pronounced in these stars, but are pretty typical in this type of RR Lyrae.

Close inspection of the change in brightness shows that these RRc variables typically have amplitudes much less than RRab types (RRab change roughly $\pm 25\%$ and RRc change roughly $\pm 10\%$).

Figure 7 shows the same type of Lomb-Scargle analysis for this star. The overall features of the

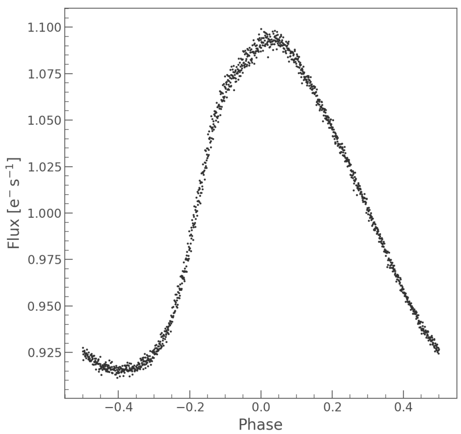

Figure 6: The phased lightcurve of an RRc type variable.

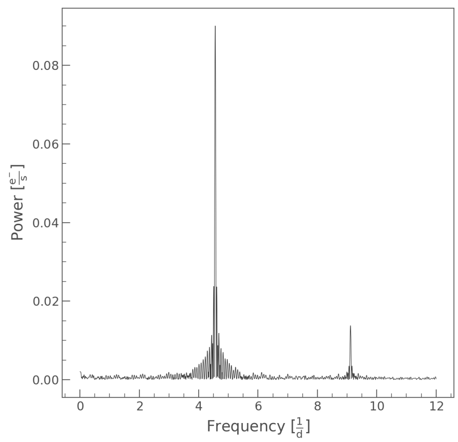

Figure 7: Lomb-Scargle analysis of the RRc star shown in Figure 6.

Lomb-Scargle analysis are similar to those for the RRab star, although this particular RRc has a pulsation period that is much shorter (frequency $\sim 4.5\ d^{-1}$) with only one harmonic seen at higher frequencies.

3.3 RRd

This type of variable tends to be the least well-behaved of the three. One can see in the phased lightcurve, shown in Figure 8, that there is not a single, well-defined oscillation for this star. The brightness at max light changes by $\sim 30\%$, while the changes in minimum brightness change by only $\sim 10\%$. This lightcurve also has a more sinusoidal shape, but the curves with the brightest max light values do look somewhat like the RRab lightcurve.

The Lomb-Scargle analysis for this star is also a much busier plot than for the two previous types. One can see the largest peak is at a frequency of slightly less than $2.5\ d^{-1}$ and the second highest peak is at a slightly lower frequency (a little more than $2\ d^{-1}$). In a similar fashion to the two previous types, the higher-order harmonics for these two peaks can be seen at higher frequencies. There are also extra peaks in this plot not seen in the others - e.g. at slightly higher than 0.25, which corresponds to the difference of the two main peaks.

4 Interesting Features

The examples shown in the previous section can be thought of as "prototypes" for those variables. They will not all look identical, but those types will all look similar and have similar features to each other. In this section, we will see what types of deviations from these "normal" examples are interesting for this research.

4.1 Blazhko Effect

Not long after their discovery as a variable source, some RR Lyrae stars were found to have a changing amplitude to their lightcurves. RR Lyr is not only the namesake of the entire group of variable stars it belongs to, but is also an example of one that changes amplitudes - a variable

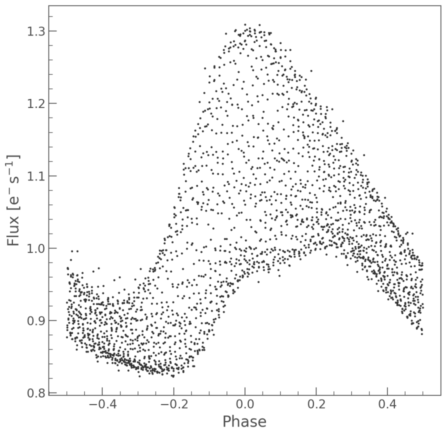

Figure 8: The phased lightcurve for an RRd type variable.

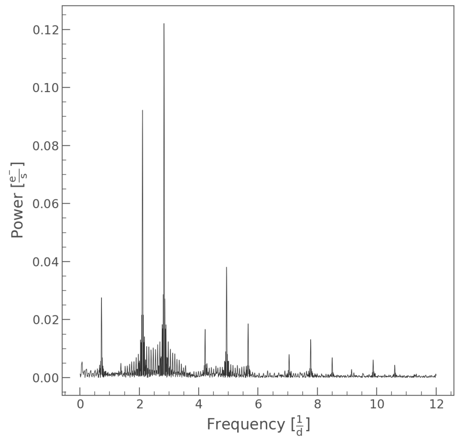

Figure 9: Lomb-Scargle analysis of the RRd type variable seen in Figure 8.

that exhibits the Blazhko effect (named after the man who discovered it). The mechanism behind the changing amplitude is unknown, but the effect can be clearly seen in long-period data of these variable stars.

In Figure 10 and 11 one can see a good example of this effect. Figure 10 is more obvious because the points are connected with lines. Figure 11 looks quite strange and the individual cycles are difficult to see. The obvious sign this is a Blazhko variable, though, is the changing maximum and minimum amplitude of the lightcurve.

In Figures 12, 13, 14, and 15 the Blazhko effect is more clear and pronounced. This is due in part to the longer time window covered in the plots, as well as the more recognizable pulsation cycle that is visible. It is important to note, however, that the phased lightcurve of these variable stars looks quite similar to a "normal" RRd type variable, such as in Figure 8. In order to distinguish between a normal RRd and a RRab with the Blazhko effect, one should notice that the shape of the lightcurve for the Blazhko star remains roughly the same, while the RRd curve does not. Also, the Lomb-Scargle analysis of the Blazhko star should show a single, primary frequency and the RRd star has peaks associated with both pulsation modes. Lastly, the amplitude changes occur smoothly and over a longer time period (days) in a Blazhko variable than the changes in the lightcurve of an RRd that arise because of the pulsation having two modes.

When looking at very long time periods, such as in Figure 16, the changing amplitude of the pulsation is clear. And if one zooms into a smaller area, such as in Figure 17, it is obvious that the lightcurve shape is remaining the same from cycle to cycle, but the amplitude of the pulsation is slowly changing.

It is important to note that changes in the amplitude of the pulsation may *not* be related to the Blazhko effect. For example, in Figure 18 there is a lightcurve where there are large changes in the apparent amplitude of this variable. Close inspection of the two regions with large amplitudes show that these sectors do not have good data and the pulsation is not obviously apparent. Also, Figure 19 shows a zoomed in view between the two regions with large amplitude, and this plot looks like a stable, "normal" RRab variable. (*NOTE*: There are very slight changes in the maximum light of this star that may be periodic, so this in fact could potentially be a Blazhko variable, although with a very small amplitude.)

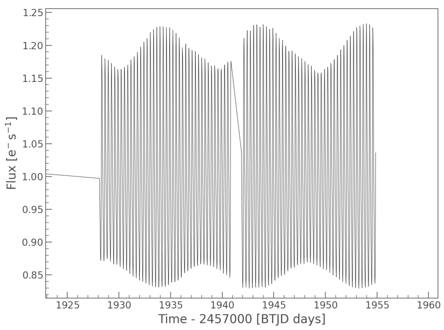

Figure 10: Lightcurve of a Blazhko type variable with lines connecting the points to aid in visibility.

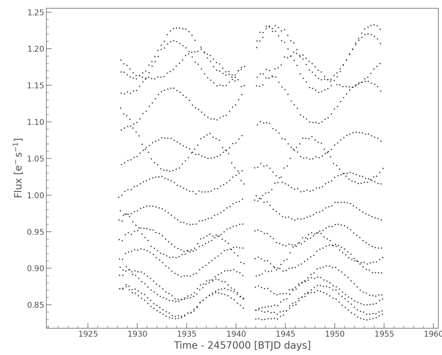

Figure 11: The same plot as Figure 10 but with only data points. This graph is much more difficult to decipher.

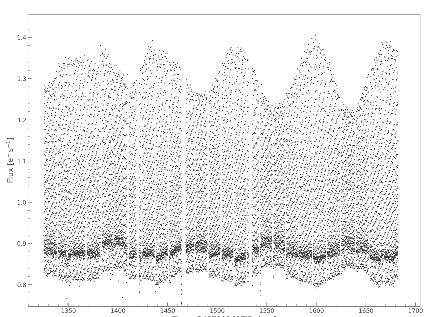

Figure 12: An example of the lightcurve of a RRab variable that exhibits a changing amplitude due to the Blazhko effect.

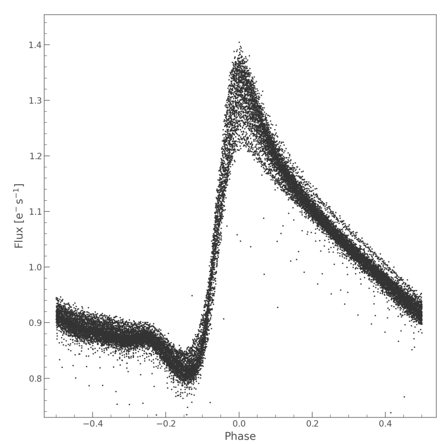

Figure 13: The phased lightcurve of the star shown in Figure 12.

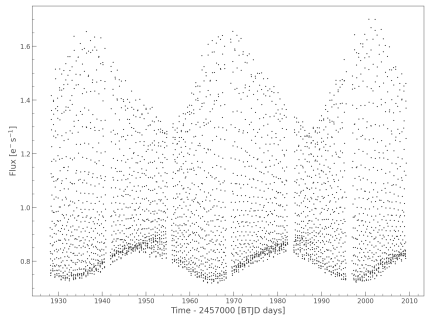

Figure 14: An example of the lightcurve of a RRab variable that exhibits a changing amplitude due to the Blazhko effect.

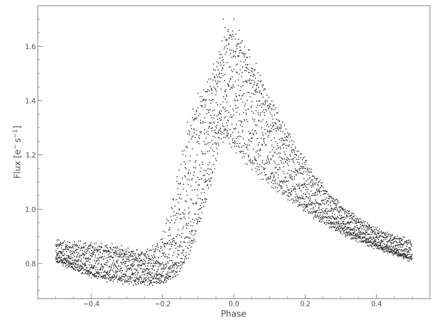

Figure 15: The phased lightcurve of the star shown in Figure 14.

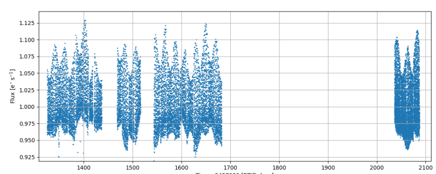

Figure 16: An example of the lightcurve of a RRab variable that exhibits a changing amplitude due to the Blazhko effect.

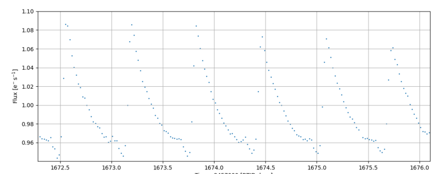

Figure 17: A zoomed in region of Figure 16 that shows several pulsation cycles for this star.

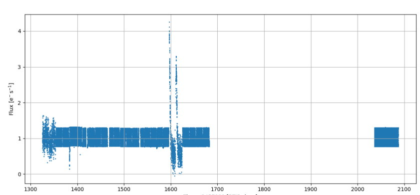

Figure 18: The lightcurve of a RRab variable with large changes in the amplitude that are *not* due to the Blazhko effect.

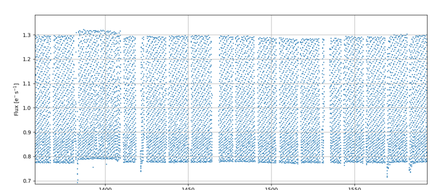

Figure 19: A zoomed in region between the large amplitude changes in Figure 18.

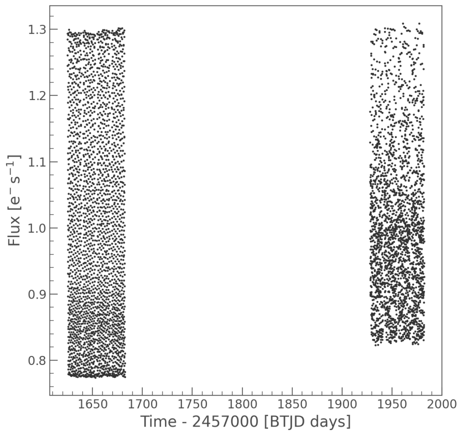

Figure 20: The potential lightcurve of a mode switching RR Lyrae.

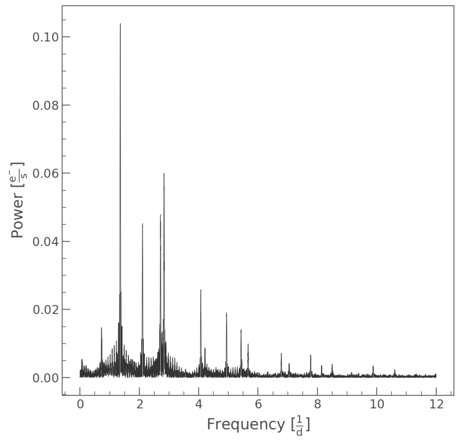

Figure 21: Lomb-Scargle analysis of the variable seen in Figure 20.

4.2 Mode Switching

There have been ~ 10 examples of RR Lyrae stars changing their mode of pulsation out of the many thousands of these variables. So, this is obviously a very rare and interesting phenomenon. All of the known examples have been from ground-based data and there was a gap of a year (or much longer) between when the star exhibited the different pulsation modes. There has *not* been an example of a star changing modes over the course of collecting data on the object.

Every known mode switching RR Lyrae has been between only two types: RRab $\leftrightarrow$ RRd. As can be seen in Section 3.1 and 3.3, the differences in the lightcurves of these two types are quite large, so the change should be easily noticeable. Since there are no examples in *TESS* data of a mode switching RR Lyrae, I have created a couple of examples of what one might look like by combining the lightcurves of two different stars.

In the first example, I have combined two stars with very different periods. You can see there are definitely some differences in the lightcurves shown in Figure 20. First of all, the left group of points are very uniform with a definite repeating pattern. The right group of points does not have the same uniformity - there are more points in the lower half and one does not see the same repeating patterns. Also, the amplitude is different between the two groups: the left group changes from ~ 0.78 to ~ 1.3 and the right group changes from ~ 0.84 to ~ 1.3. It is important to note that changes in the amplitude *do not necessarily* mean a mode switch has happened (see Section 4.1) but it is a feature that should be further explored to see if the actual lightcurve has changed. Another piece of evidence of a mode switch will be in the Lomb-Scargle analysis. As seen in Figure 21, the analysis shows multiple peaks. Because these have different periods, one sees the main peak and harmonics for the RRab pulsation separately from the two RRd main peaks and their harmonics: the tallest peak at $\sim 1.5\ d^{-1}$ is the RRab pulsation and the taller peak at $\sim 3\ d^{-1}$ along with the peak at just over $2\ d^{-1}$ are the two main peaks of the RRd pulsation.

A primary pulsation period that changes very little seems much more likely in mode switching RR Lyrae (one reference that finds three examples claims there is a slight increase in the fundamental mode period when going from RRd to RRab and a slight decrease in the opposite change, but the changes were very small with the largest being $\sim 0.002\ d$, which is just under three minutes). Therefore, in Figures 22, 23, 24, and 25 are plots showing a mode switch with a small change in the main pulsation period. There are changes in the amplitude and uniformity of the lightcurve, similar to those from the previous example. More importantly, though, the changes in the Lomb-Scargle analysis are harder to notice. Figure 23 shows the full range in the x-axis, and this plot looks very similar to Figure 9 at first glance. Closer inspection of the largest peak and its first harmonic show that there is another peak very nearby. Figures 24 and 25 are zoomed in portions of the plot for the primary and first harmonic region, respectively. The slight difference is magnified in the harmonics, but are still small features. It is important to note, however, that even this small change is much larger than what is probable for a mode switching RR Lyrae, so in all likelihood there will be no additional peak. This means that one may only see a "normal" RRd Lomb-Scargle analysis but two different types of pulsations in the lightcurve.

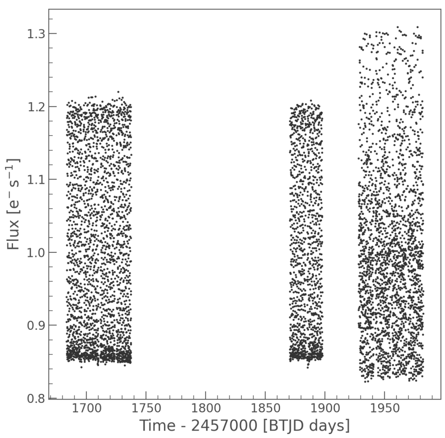

Figure 22: The potential lightcurve of a mode switching RR Lyrae.

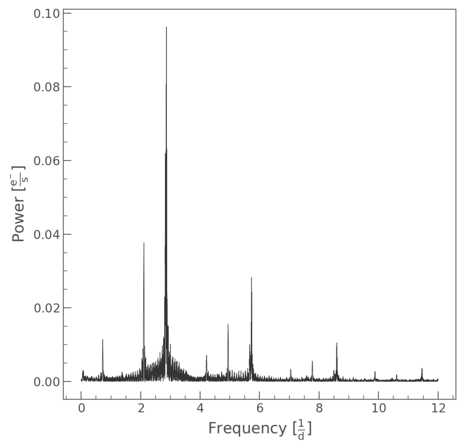

Figure 23: Lomb-Scargle analysis of the variable seen in Figure 22.

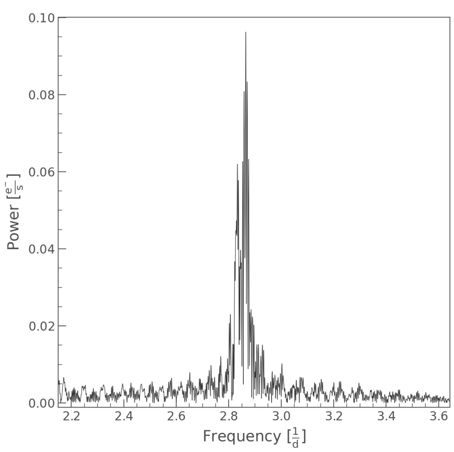

Figure 24: Zoomed in region of the primary peak in Figure 23.

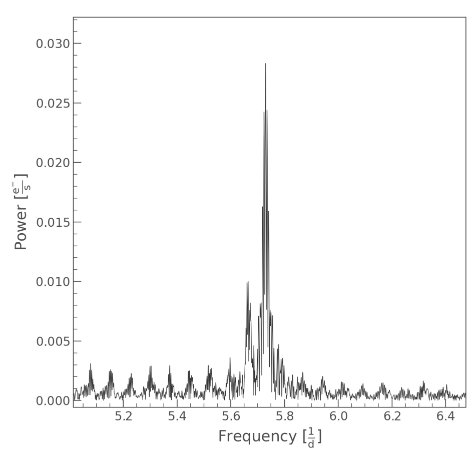

Figure 25: Zoomed in region of the first harmonic of the primary peak in Figure 23.

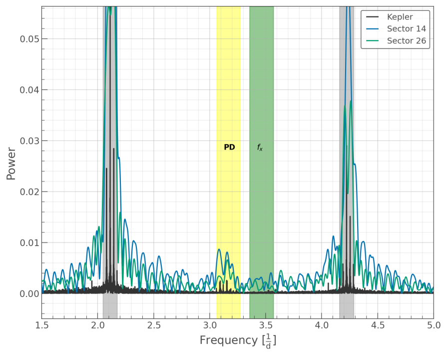

Figure 26: A plot showing a peak in the yellow shaded region, which corresponds to period doubling in RR Lyrae.

4.3 Period Doubling

The discovery of period doubling in RR Lyrae was relatively recent. This phenomenon is not easily seen from the ground because cycle-to-cycle changes are not visible when one sees every other pulsation because of the day/night cycle and the ∼0.5 day period of RR Lyrae. The continuous coverage from *TESS* clearly shows a changing amplitude from one cycle to the next in some of these stars, and peaks in the Lomb-Scargle analysis allow us to easily identify them.

The science of why period doubling occurs is very interesting, but we are mainly interested in finding the behavior in RR Lyrae types. In Figure 26 one can see how we identify these stars. This figure has data from *Kepler* as well as *TESS*, and the yellow and green shaded regions are the same as those found in the GUI. The *Kepler* data shows more detail and structure, but *TESS* data clearly has a peak (or really multiple peaks) in the yellow shaded region. When there is an obvious signal above the background in the yellow shaded region, that option should be marked "YES". It may not be a single, well-defined, sharp peak, and it may be on the edges of the shaded region, but any signal in this region should be marked as "YES".

4.4 Non-radial Modes

The green shaded region in the GUI corresponds to another interesting phenomenon only discovered because of space-based observations. RR Lyrae type stars pulsate in either the fundamental or the first overtone radial modes (or both in the case of RRd). However, with continuous, high cadence, space-based observations, additional peaks in the Fourier analysis of an RR Lyrae can be seen. In Section 4.3 we saw one example of these additional peaks, which are highlighted by the yellow region in the GUI. Peaks occurring in the green shaded region are thought to be due to resonances between the normal pulsation modes and higher-order non-radial pulsations.

Similar to the period doubling (yellow) region, any kind of signal in the green region should be marked "YES". These peaks may be more defined than those seen for period doubling, but they can occur anywhere in the shaded region, and even if they are on the edge they should be marked "YES".

4.5 Closing Remarks

With this GUI we are able to accomplish several tasks. We can provide a type for an RR Lyrae variable, we can determine a good value for the pulsation of the star, we can look for variations in the amplitude of the pulsation, and we can look for indications of smaller changes occurring within the star.

One must keep in mind, however, that this GUI is a blunt object that we are using to examine many examples of a type of star that can exhibit strange behavior. Some of the RR Lyrae may be the proverbial square peg trying to fit into a round hole. Time and consideration must be taken to try to give the best results, but for any unusual behavior there is a place for "Notes" to record terse comments about the star. Terse here is important, because there is currently a 250 *character* (**not** word) limit for this field. Note any uncertainty or other comments here so followup analysis can be done.