Searching for RR Lyrae Variables in the Dark Energy Survey

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Abstract

RR Lyrae variables are stars with a characteristic relationship between magnitude and phase and whose distances can be easily determined, making them extremely valuable in mapping and analyzing galactic substructure. We present our method of searching for RR Lyrae variable stars using data extracted from the Dark Energy Survey (DES). The DES probes for stars as faint as i = 24.3. Finding such distant RR Lyrae allows for the discovery of objects such as dwarf spheroidal tidal streams and dwarf galaxies; in fact, at least one RR Lyrae has been discovered in each of the probed dwarf spheroidal galaxies orbiting the Milky Way (Baker & Willman 2015). In turn, these discoveries may ultimately resolve the well-known missing satellite problem, in which theoretical simulations predict many more dwarf satellites than are observed in the local Universe. Using the Lomb-Scargle periodogram to determine the period of the star being analyzed, we could display the relationship between magnitude and phase and visually determine if the star being analyzed was an RR Lyrae. We began the search in frequently observed regions of the DES footprint, known as the supernova fields. We then moved our search to known dwarf galaxies found during the second year of the DES. Unfortunately, we did not discover RR Lyrae in the probed dwarf galaxies; this method should be tried again once more observations are taken in the DES.

Introduction

The first, obvious question to consider when locating RR Lyrae is how one can distinguish RR Lyrae variables stars from the thousands of other stars one may find when probing a small area of the DES. In general, RR Lyrae lie in a relatively well-defined region on color-color plots, and Sesar et al. 2010 determined these color cuts to be effective:

$$-0.15 < g - r < 0.40$$
$$-0.15 < r - i < 0.22$$
$$-0.21 < i - z < 0.25$$

The variability cuts were determined based on the following low order statistics and the bounds on these statistics (Sesar et al. 2010):

$$\chi^2 = \frac{1}{n-1}\sum_{i=1}^{n}\frac{(x_i - mean(x))^2}{\delta_i^2}$$

$$\gamma_g = \frac{n^2}{(n-1)(n-2)}\frac{\mu_3}{\Sigma^3}$$

$$\sigma = [\Sigma^2 - mean(\delta)^2]^{\frac{1}{2}}$$

Where

$$\mu_3 = \frac{1}{n}\sum_{i=1}^{n}(x_i - mean(x))^3$$

$$\Sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - mean(x))^2}$$

Finally, we required $\chi^2(g) > 3,\ \chi^2(r) > 3, \sigma(g) > 0.05, \sigma(r) > 0.05, \gamma_g > 1$

Where n is the number of observations for the band considered, x_i represents the magnitude, δ_i represents the error in the magnitude, g represents the g band magnitudes, and r represents the r band magnitudes.

Using the period found upon implementing VanderPlas' pythonic implementation of the Lomb-Scargle Periodogram, we subtract from the time of each observation the first observation, modulo period. This maps all the points in the light curve to a point on the magnitude vs. phase plot, producing a characteristic light curve if the object being analyzed is RR Lyrae.

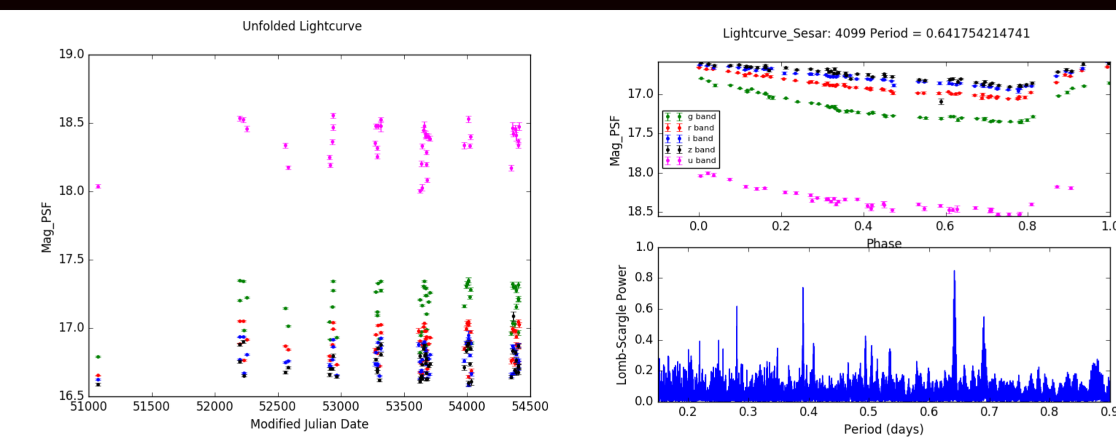

Figure 1: An example of a "ground truth" RR Lyrae variable with its unfolded and folded light curves.

Looking for RR Lyrae in Supernova Fields

With the periodogram functioning as desired (see right hand plot), we then moved our focus on actually finding RR Lyrae in the Dark Energy Survey. The Dark Energy Survey consists of two different methods of probing the sky, the wide-area and the time-domain surveys. The wide-area survey intends to cover a large area of the sky below the celestial equator (5000 squared degrees of sky, to be exact). To begin our search, we analyzed data from the Supernova fields within the DES Survey (these fields are circled in yellow in plot below), as these fields have a much higher number of observations in the DES Survey. A typical number of observations in the Supernova Fields is 100 or more, whereas the Y1 and Y2 data typically have a maximum of twenty observations per object, and these areas of the survey do not overlap.

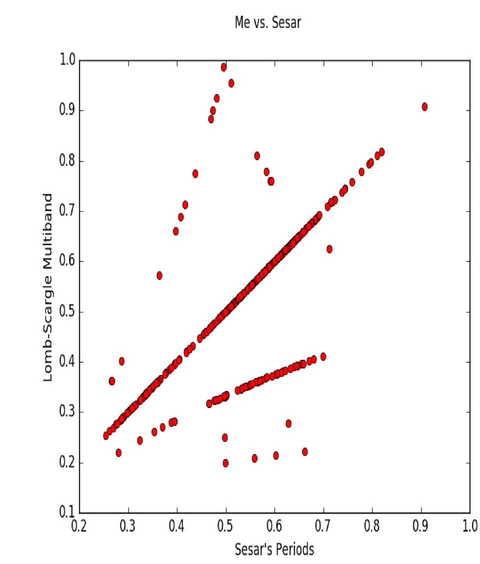

Figure 2: Demonstration of the functionality of the Lomb-Scargle Multiband Periodogram with periods from Sesar et al. 2010 as "ground truth".

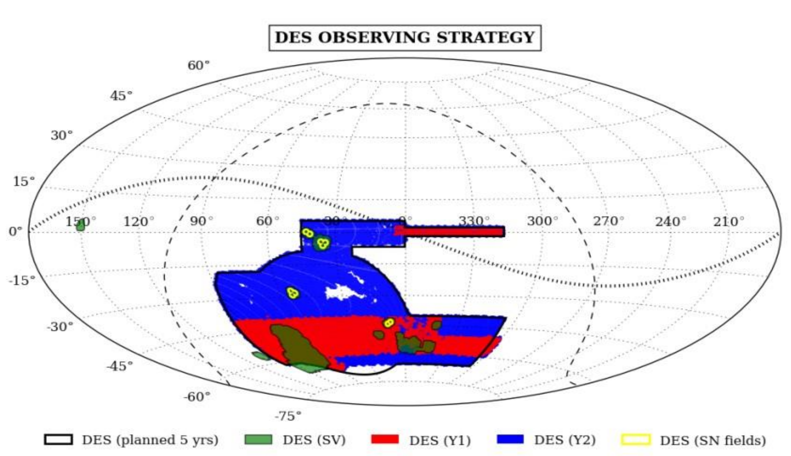

Figure 3: The DES Footprint illustrating the areas of observation in the survey. Our focus was on the Supernova Fields (yellow circles). We then moved to study dwarf satellites in the Y1 and Y2 areas of observation. This plot is credited to Abbott et. al 2016

Thus begun the search for the RR Lyrae in the Supernova Fields. We began the search in Stripe 82, an area of the sky with a low declination (declination is representative of any vertical change in the graph above). Upon the completion of this poster, five of the supernova fields had been analyzed, which represents approximately 15 squared degrees of sky. Some results characteristic of the search are below.

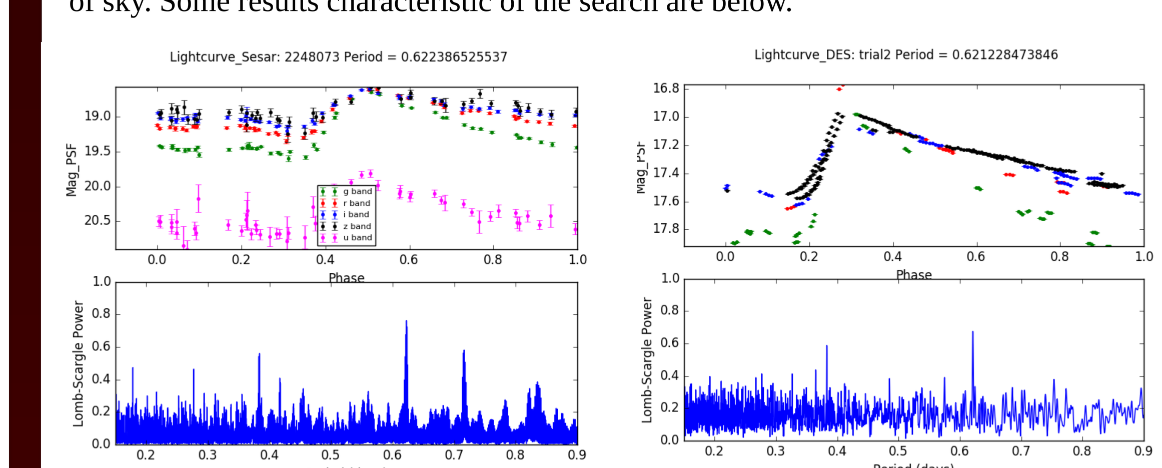

Figure 4. A "ground truth" RR Lyrae variable compared to an RR Lyrae found in the Supernova Fields of the Dark Energy Survey. Note the characteristic asymmetric form of the folded light curve in both. The RR Lyrae we found in the DES data had already been detected when we found it.

After one scan of these five fields for RR Lyrae variables, we conducted the search again without the lightcurve skewness cut ($\gamma_g > 1$), for we feared we were lacking our sample lacked completeness due to this cut. However, this resulted in some ambiguous RR Lyrae candidates, and occasionally clever thinking was required to determine if the plotted light curve was indeed an RR Lyrae. In addition to the asymmetric folded light curve of an RRab star (displayed above), there exists a type of RR Lyrae with a more sinusoidal form, called an RRc star.

While these stars are far more rare than RRab type stars, we could not rule out a potential detection. Unfortunately, however, these stars have light curves very similar to eclipsing binary stars, and these were specifically cut using the condition $\gamma_g > 1$. One such ambiguous case is displayed below:

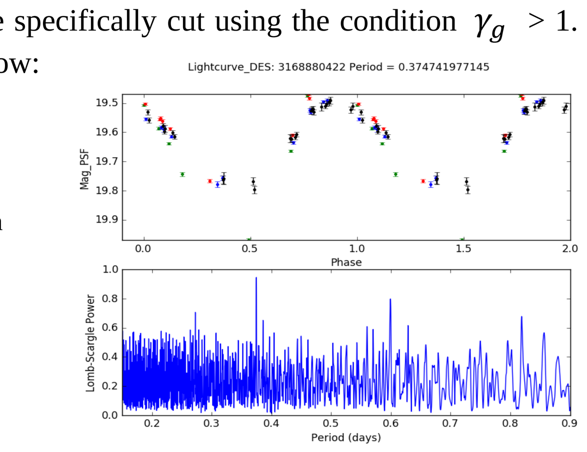

Figure 5: Determining if a star as shown is indeed an RR Lyrae. After much thought, it was realized that such a star is likely not an RR Lyrae, as the color does not change with respect to phase. This plot is most likely an eclipsing binary.

Other problems were encountered while searching for RR Lyrae variables. One such problem is aliasing. The DES Survey has an observing cadence of approximately one day, and the frequency with which we took measurements may lead the periodogram to conclude that the period is different than the true period of the object. In particular, the periodogram would return periods that are harmonics of one day (1/2 day, 1/3 day, …)

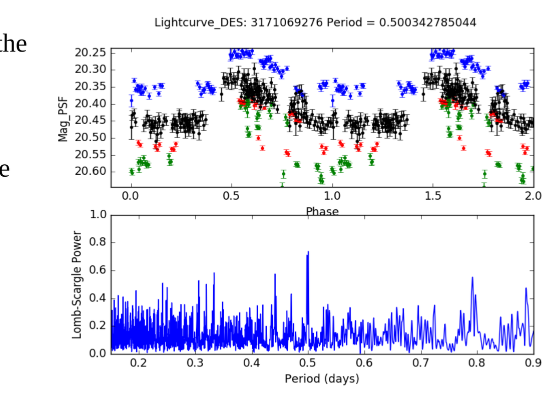

Figure 6: An example of a light curve with the characteristic asymmetric of an RRab star. Initially, this was thought to be a detection, but upon further thought that this curve may be distorted/be in error due to aliasing effects. Note the proximity of the calculated period to ½ day. Such effects were analyzed further after this poster was developed; namely, we would set to zero any Periods that were in some small neighborhood of 1/2 day, 1/3 day, etc.

From this point, we chose to shift our attention to dwarf satellite galaxies orbiting the Milky Way. The discovery of such satellites is important, as theory predicts far more satellite galaxies than are observed. One RR Lyrae has been found in every dwarf satellite discovered, so it is scientifically significant to discover such an RR Lyrae in such a dwarf galaxy.

Dwarf Galaxies

Unfortunately, none of the identified or candidate dwarf galaxies can be found in the Supernova Fields, so the number of observations for a field containing a dwarf galaxy is extremely limited. While the Supernova Fields may have 400 or more observations per object, the stars of a dwarf galaxy typically have between 18 and 25 observations. To test the Lomb-Scargle Periodogram, we found a star with a similar number of observations to those stars in a dwarf galaxy. The results were less than satisfactory:

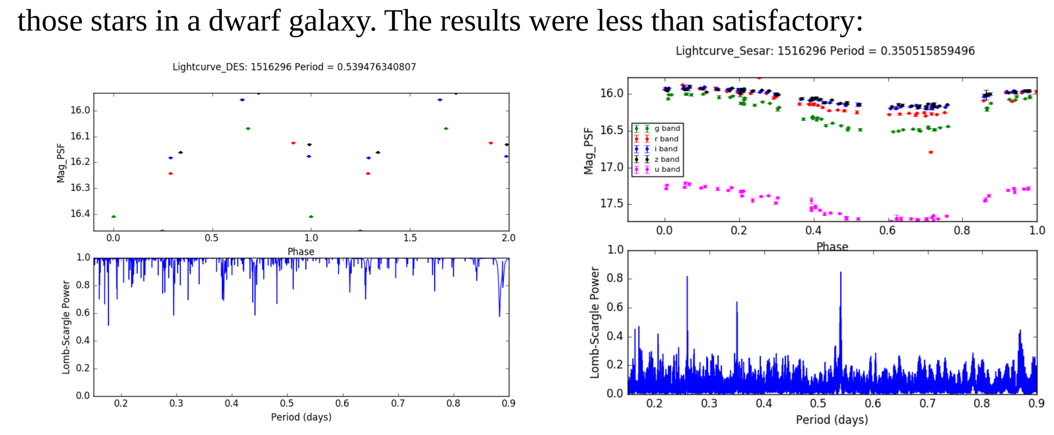

Figure 7: Our method completely fails when applied to very sparsely sampled stars (n <= 25). The right-hand plot is due to Sesar et al. 2010 and represents a "ground-truth" RR Lyrae, while the star on the left is one whose right ascension and declination differs from the Sesar star by 0.000012 and 0.000009 degrees, respectively (in other words, these are very likely to be the same star). Furthermore, their r band magnitudes differ only by 0.07.

Figure 7 comically demonstrates the complete failure of the Lomb-Scargle Periodogram to recover the correct period. By the end of the DES, there will be at least 40 – 50 observations per object (assuming DES probes the area as it has in Y1 and Y2). It will then be more plausible to utilize this method on all 5000 squared degrees of sky to search for RR Lyrae in the dwarf galaxies and beyond.

Conclusions

We have described our method of identifying RR Lyrae variable stars in the Dark Energy Survey. We demonstrated the ability of Vanderplas' implementation of the Lomb-Scargle Periodogram to correctly identify periods, showed that RR Lyrae can be identified in the DES, and described some of the caveats of utilizing this method for the purpose of identifying RR Lyrae. Unfortunately we did not have the opportunity to analyze the dwarf galaxies in the DES for RR Lyrae; yet, once the survey is complete, there will be a sufficient number of observations to employ this method and obtain important scientific results. Namely, we will be able to measure the distance to such galaxies very accurately.

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Acknowledgments

Texas A&M University thanks Charles R. '62 and Judith G. Munnerlyn, George P. '40 and Cynthia Woods Mitchell, and their families for support of astronomical instrumentation activities in the Department of Physics and Astronomy.
This work was supported by NSF grant AST-1263034, "REU Site: Astronomical Research and Instrumentation at Texas A&M University."