

Searching for RR Lyrae Stars in M15

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Khalid Kayal

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Abstract

The expansion and contraction of an RR Lyrae star provides a high level of interest to research in astronomy because of the several intrinsic properties that can be studied. We did a systematic search for RR Lyrae stars in the globular cluster M15 using the Catalina Real-time Transient Survey (CRTS). The CRTS searches for rapidly moving Near Earth Objects and stationary optical transients. We created an algorithm to create a hexagonal tiling grid to search the area around a given sky coordinate. We recover light curve plots that are produced by the CRTS and, using the Lafler-Kinman search algorithm, we determine the period, which allows us to identify RR Lyrae stars. We report the results of this search.

Glossary of Abbreviations and Symbols

| | |
|------------|-------------------------------------|
| CRTS | Catalina Real-time Transient Survey |
| RR | A type of variable star |
| M15 | Messier 15 |
| RA | Right Ascension |
| DEC | Declination |
| RF | Radio frequency |
| GC | Globular cluster |
| H-R | Hertzsprung-Russell |
| SDSS | Sloan Digital Sky Survey |
| CCD | Couple-Charged Device |
| Photcat DB | Photometry Catalog Database |
| FAP | False Alarm Probability |

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1 Introduction

RR Lyrae stars are low-mass variable stars, around 10-14 Gyr old, that pulsate radially with short periods. They were first discovered in nearby globular clusters about a 120 years ago. Today, around 1,500 RR Lyrae stars have been found in globular clusters (GCs) and around 6,000 isolated stars are known to be RR Lyrae [5]. They pulsate in radius and luminosity over short periods; the brightness rising quickly to its peak followed by a slow and gradual drop. These stars take around 10 billion years to completely evolve into the RR Lyrae stage. The ionization of helium in its shells blocks photons, or radiation, from completely escaping the star due to how dense or opaque the star's gas becomes. Gravity brings the star back to its original state and the cycle repeats. We can start doing a detailed study of the period and learn about the metallicity and the distance to globular clusters.

Here we focus on searching for RR Lyrae stars in a particular globular cluster—NGC 7078, or Messier 15 (M15). Globular clusters are dense groups of old stars that have formed a gravitationally bound spherical shape. They contain hundreds of thousands of stars and orbit the center of our galaxy. M15 holds a high level of interest due to a potential intermediate black hole at its core; it's also a core-collapsed globular cluster [2], but there is also evidence that is contrary to the existence of this black hole [4]. This would affect the positions of these variable stars and possibly lead them to the outskirts of the GC.

I've created a hexagonal tiling algorithm using the programming language, Python. It functions to zone into the galactic sky after inputting a position—Right Ascension (RA) and Declination(DEC)—and creates a circle around the coordinate with a default radius (1.5 arcseconds), and then produces successive circles around the given point. These circles have a predetermined offset that allows the entire area of interest to be completely covered. Tilings levels are created based on how large of an area that will be searched. Once the desired tiling is reached, the code will then output the coordinates of the centers of all circles produced into an ASCII file. Once the sky coordinates are attained, the CRTS is used to effectively retrieve, and later download, the photometry of each point. The Catalina Real-timeTransient survey (CRTS)—which I'll go into detail in Chapter 3—allows us to commence a detailed search for light curves at a point of interest, given that it is within the sky covered. Once the light curves for various sources are obtained, the Lafler-Kinman method [3] is used to identify periodic features

of a light curve by taking the square distance between the two closest points on the curve. The correct period is then found by determining the minimum distance, which helps us identify the RR Lyrae stars.

The Hertzsprung-Russell (H-R) diagram is a graph displaying the relationship stars have between their luminosities and spectral types, which corresponds to the star's effective temperature. They're known as color-magnitude diagrams. The surface temperature varies as well as the apparent magnitude since we're dealing with pulsating variables, so the class for RR Lyrae stars goes from spectral type A8 to F7. This also places them on what is known as the horizontal branch of the H-R diagram. The horizontal branch stage is known as the core helium burning phase. In color-magnitudes of globular clusters, there lies an empty region where stars seem to be missing. This is known as the RR Lyrae Gap. It's not that the stars aren't there, we know they are, but that because of their variations in magnitude—sometimes between a whole magnitude—they aren't plotted. This gap is part of what is known as the Instability strip.

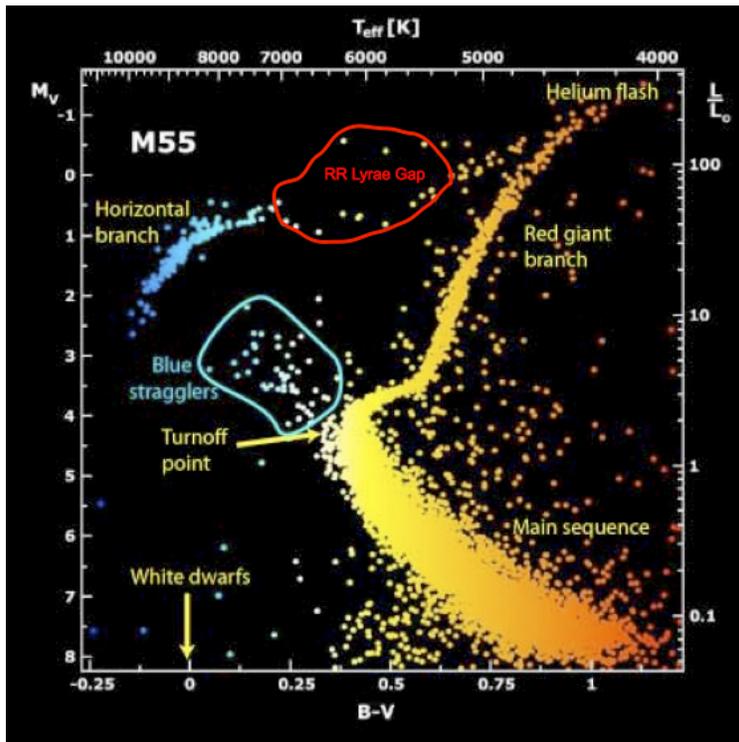


Figure 1: H-R Diagram displaying the RR Lyrae Gap

RR Lyrae stars are located inside the Instability strip—which crosses the horizontal branch. The Instability strip is a narrow region on the Hertzsprung-Russell diagram where pulsating, or throbbing, variable stars exist. Not all stars on the horizontal branch are variable stars, though; only those that exist with the Instability strip. These stars steer off the red giant branch on the H-R diagram when they start to experience ionization of helium in their shells. The star enters the stage where singly ionized helium (He II) turns into doubly ionized helium (He III) and vice-versa. The reason behind these pulsations deals with the He III forming in the composition of the star. He III loses all of its electrons and can therefore no longer be ionized. The second ionization stage occurs when the star contracts, since the density and temperature increase. This makes it difficult for photons to escape these He III shells due to the increased opacity that results. Once the star begins to expand, the He III recombines into He II and the clouds become less dense and the star cools down.

Metallicity deals with the chemical composition of a star. It is the fraction of the star that contains elements other than hydrogen and helium. It essentially measures the number of times the gas has been reprocessed through previous generations of stars. As mentioned before, RR Lyrae stars are constantly switching between ionization levels in helium. The abundance of helium is also believed to be important in determining the course of evolution and pulsation properties of an RR Lyrae star. Since a RR Lyrae star is a relatively low-mass star, nucleosynthesis of several amounts of elements heavier than carbon and oxygen is not expected during its lifetime. Therefore, RR Lyrae have low metallicities and are believed to directly reflect the abundance of heavy elements in the gas cloud from which it was formed. This indicates that the GC they reside in must also share a similar chemical composition and, in turn, is very old. It is these properties that make RR Lyrae stars useful tracers of chemical composition. Metallicity is one of the primary parameters that astronomers have used to classify an entire cluster of stars. This way, if we view changes in metallicity throughout a globular cluster, we can assert that it's been through at least two star formation periods. The color of the star is the other variable taken into consideration. The following is used to calculate metallicity:

$$[\text{Fe}/\text{H}] = \log_{10} \left(\frac{N_{\text{Fe}}}{N_{\text{H}}} \right)_{\text{star}} - \log_{10} \left(\frac{N_{\text{Fe}}}{N_{\text{H}}} \right)_{\text{sun}} \quad (1)$$

where $[\text{Fe}/\text{H}]$ is the ratio of iron to hydrogen in the photosphere of one star

which related to that ratio in another star, usually—and in this case—the Sun. So, stars that have a higher metallicity than the Sun will produce a positive logarithmic value. For metal-rich RR Lyrae stars, this value is near, but sometimes below $[\text{Fe}/\text{H}] = 0$ while the value for metal-poor RR Lyrae stars is near $[\text{Fe}/\text{H}] = -2.5$

The distance modulus to a celestial object is the difference between its apparent magnitude and its absolute magnitude. The apparent magnitude of an object is how luminous an object is as seen from Earth while the absolute magnitude of an object is what the apparent magnitude would be if the source was located 10 parsecs away from us. The distance modulus helps in determining distances and magnitudes to various objects. This very convenient for us since RR Lyrae stars have an average absolute magnitude of ~ 0.5 . The reason for this shared absolute magnitude is that RR Lyrae stars, in any given globular cluster, show only a small range in mean brightness. This makes RR Lyrae stars very useful in distance measurements and can be used as “standard candles” in the sky. Arriving at the distance modulus will be described in Chapter 4.

The visual apparent magnitude of RR Lyrae stars in M15, found from the Harris Catalog, is 15.83. That allows me to establish the effective range of apparent magnitude I’m looking for in these searches; in this case, it’s 15.83 ± 1.5 . Since we know that typical RR Lyrae range between, and sometimes a little over, a whole magnitude [5], the extra 0.5 ensures a safe and thorough search when sifting through the sources. The method in which I determine the radius of each circle produced by my tiling algorithm involves experimenting with an arbitrary radius, in arcminutes. I take the value of the radius prior to the one that informs me that there are too many sources to display (maximum is at 75). I then multiply the value by the offset between each circular region, found to be $\sqrt{3}$, and input the new radius accordingly until I’ve covered the entire area to be searched. The default radius I finally arrived at was 1.5 arcminutes.

2 Background on RR Lyrae Stars

2.1 What are RR Lyraes?

RR Lyrae stars are special kinds of stars that undergo rapid changes in luminosity due to the regular, periodic pulsation of the star. The name comes from the fact that RR indicates that it is a variable star with variations in brightness and that the first of these stars were found in the constellation Lyrae. The period for these pulsations are surprisingly small, ranging from a couple of hours to about a day. This means that magnitude observations for these variable stars can be completed over a very short period of time—a whole magnitude in change over a few hours! RR Lyrae stars also all have an average absolute magnitude of ~ 0.5 . The absolute magnitude tells us how bright a star would be if it was a certain distance away from us. This makes it extremely convenient to determine distances, with accuracy, to these stars by comparing the apparent and absolute magnitudes. This is a unique feature of these types of variable stars. The following is the luminosity-surface temperature relationship:

$$L = 4\pi\sigma R^2 T^4 \quad (2)$$

where σ is the Stefan-Boltzmann constant, R is the radius of the star, and T is the star's effective temperature.

The intensity of the light a star radiates relies on the surface area of the star and the temperature of that star. The pulsation in RR Lyrae stars occurs when the star enters a physically unstable state internally causing its surface to move in and out causing it to change in terms of size and luminosity. From what has been mentioned thus far, the changing size of the RR Lyrae star would make it the brightest when fully expanded and the dimmest once contracted but this isn't the case for we haven't considered what is happening to the temperature of the RR Lyrae star while it pulsates. As the RR Lyrae contracts, the surface heats up, and the gas is getting compressed into a reduced volume effectively increasing temperature. And as the RR Lyrae's surface expands, the pressure is released and the star cools down. It is known that from the rate at which RR Lyrae stars pulsate that their size cannot be changing sufficiently to cause the change in luminosity observed (the rate at which the size is changing is not fast enough for the amount of change in brightness that is observed.). It is the effect of change

in surface temperature along with changes in size that affects the luminosity of RR Lyrae stars. The temperature of the RR Lyrae's surface changes enough to account for the change in brightness though. So the RR Lyrae star is hottest, and brightest, when smallest in size and coolest, and faintest, when it maximizes in size.

2.2 Types of RR Lyrae Stars

RR Lyrae stars can be separated into two types: the AB type RR Lyrae (RRab) and the C type RR Lyrae star (RRc). The shape of their light curve is the principal criterion for classification. RRc type variables actually undergo expansion and contraction simultaneously, a phenomena in which the light curves well-resemble that of a sinusoid. RRab stars pulsate in the fundamental radial mode while RRc stars pulsate in the first overtone radial mode. In the fundamental radial mode, the gases move in the same direction at every point in the star [1]. In the first overtone radial mode, the gasses move in opposite directions on either side of the node [1]. A star's node is located at the center of the star (the closed end). But when a star is in the first overtone mode, a second node exists that is located somewhere in the atmosphere of the star. Typically, RRab stars exhibit cooler surface temperatures than RRc stars and are actually more common. While 91 percent of known RR Lyrae stars are of type RRab, only 9 percent are of the type RRc [5].

RRab stars are classified into one group rather than RRa and RRb because of the similar characteristics they share. The light curve of a RRb tends to be not as steep as one of a RRa (which are very steep) and also contains a flatter peak. The increase of light for RRa stars is very rapid while the increase for RRb stars is somewhat rapid. The decrease in light occurs rapidly for RRa stars and the decrease in light for RRb stars is relatively slow. The periods for RRa stars typically range from twelve to fifteen hours while the periods for RRb stars range from fifteen to twenty hours. The main reason for the grouping is that the change in amplitudes of RRa stars range to a little over one magnitude while RRb stars range to around 0.9 magnitude. These small variations in parameters, along with the fact that they both pulsate in the same radial mode, allows us to group the two classes, RRa and RRb, together. There are subtle differences regarding the location of the driving force in RRab and RRc stars (where the ionization layer exists).

RRc stars, on the other hand, have a lower average amplitude at around

0.5 in magnitude. In this class, light seems to be constantly changing—sinusoidally—and with moderate rapidity. The increase of light for a RRc star is slightly more rapid than the decrease. There are rare exceptions where the opposite is true and sometimes, the change in light is equal. The periods for RRc stars are usually from eight to ten hours. The following diagram shows general plots:

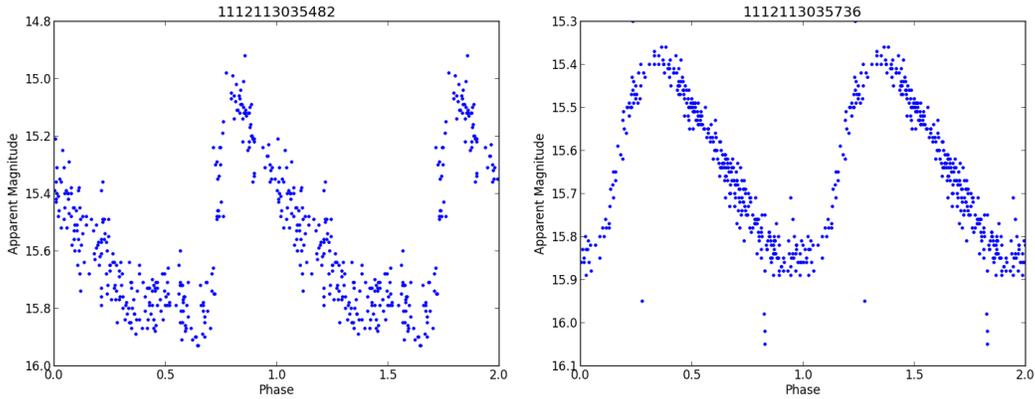


Figure 2: Examples of a RRab star and a RRc, respectively

Because of the characteristics stated, the average period of a RRab stars tends to be ~ 0.7 days and RRc stars have an average period of ~ 0.3 days. Asteroseismology is the study of the pulsation modes of stars in order to investigate their internal structures, chemical composition, rotation, and magnetic fields. It can be used to further investigate the pulsation mechanism of these RRab and RRc stars.

There is an additional observed variation called The Blazhko effect. This happens when a variation in amplitude and the period exists in variable stars. Some RRab stars display signs of the Blazhko effect while it is very rare in RRc stars. The two main theories to date trying to explain the Blazhko effect are Stohers and Preston [5]. Stohers states the the changes in period is induced by the convective envelope while Preston claims it's interference of radial and non-radial modes of similar frequency. Further explanation of this effect is found in Appendix A.

2.3 Stellar Evolution

RR Lyrae stars are not variable stars their whole lives. Instead, they are formed as a result of stellar evolution. RR Lyrae stars evolve the way low-mass stars are expected to. A RR Lyrae star is believed to have started off as a main sequence star with a mass around $0.8 M_{\odot}$. The progenitor of a RR Lyrae star spends the majority of its energy-producing lifetime on the main sequence and fuses hydrogen to helium in its core. After an extensive period of time, hydrogen in the core becomes depleted and the star steers into the red giant branch, all the while burning hydrogen to helium in a shell surrounding a helium core. The temperatures in these cores are still not high enough to continue nucleosynthesis so the inert core collapses. The electrons in the core are now compressed very tightly and the number of available low energy states is too small so many electrons are forced into higher energy states. This makes the electrons degenerate which make a significant contribution to the pressure due to their high energy states. Since this pressure arises from a quantum mechanical effect, it is unaffected by temperature—meaning that pressure doesn't decrease as the star cools down. At the beginning of the red giant branch, the temperature in the core becomes high enough to start helium fusion. The core's temperature continues to increase until it reaches a point where helium atoms actually fuse together to produce carbon—known as the triple alpha process. In this “helium flash,” helium starts to burn in the electron degenerate core through the triple alpha process which removes the degenerate core. The star then migrates to the horizontal branch and enters the stage in its life where it burns helium in its core. If the star falls within the instability strip, it becomes an RR Lyrae variable type star. At this point, the star's radius is four to six times the radius of the Sun, but is still less massive than the Sun and nowhere near as big or bright when compared to its stage in the red giant branch.

As with all stars, a RR Lyrae will eventually reach the end of its life. In the case of RR Lyrae stars, this occurs when the central helium in the star is completely depleted, which usually takes about 100 Myr after the star begins the core helium burning phase. The star leaves the horizontal branch when the core begins to exhaust its helium, and ascends up the red giant branch, deriving its energy from a hydrogen burning shell and a helium burning shell. The red giant will inevitably run out of available nuclear fuel and its central temperature will never again become high enough for the fusion of heavier elements to begin in its carbon and oxygen core. The star

then forms into a white dwarf after expelling its outer gaseous envelope. The white dwarf will then continue to gradually radiate all of its internal heat energy.

2.4 Pulsating Mechanism

The following briefly explains the pulsation mechanism of RR Lyrae stars and how they work internally. When the star is compressed or contracted state, the He II in the atmosphere of the star ionizes into He III. This leads to the gas clouds being less transparent and way more opaque. The opacity of a star determines how easily photons can pass through the star in its layers; it is the reciprocal of transparency. When photons are withheld, the RR Lyrae star heats up with an increase in temperature which, in turn, causes the stars to expand. On the other hand, if photons escape due to low opacity, the RR Lyrae star cools down with a lower gas pressure that allows gravity to compress the star. The overall opacity of a region in a star can be identified by κ , the Rosseland mean opacity. The temperature and density dependency of this variable can be described by the following relationship:

$$\kappa = \kappa_0 \rho^n T^{-s} \quad (3)$$

where κ_0 is a constant, ρ is the star's density, and T is the temperature of the star. When no important element is experiencing ionization in the gas located in the stellar envelope, $n \approx 1$ and $s \approx 3.5$. But this states that T is inversely proportional to the opacity, which is not the case with RR Lyrae stars. However, if an abundant element is being ionized in some region, the value of s can become small, sometimes negative. Therefore, the gas in this region is now mostly opaque near the peak of compression. This is known as the κ -mechanism and is a form of Kramers' Law, but with the proportionality constant included. The other main mechanism that is connected with the ionization zones in RR Lyrae stars and contributes to the driving force is the γ -mechanism. In this scenario, the energy that would usually raise the temperature is absorbed by the ionizing matter. Therefore, the layer tends to absorb heat during compression, which leads to a driving force for the pulsations.

To recap: When this pressure exceeds the internal gravitational force of the star, the star then begins to expand. The atmosphere then starts cooling

down and the He III gains an electron to become He II again, leading to increase in the transparency of the atmosphere, which, as previously mentioned, allows for the pressure to decrease and the star to contract once more. The cycle repeats.

3 Useful Tools and Surveys

3.1 Choosing M15

Globular clusters (GCs) are massive, spherical concentrations of stars that are bound by gravity and orbit a galactic core. These clusters are typically ~ 100 light years across. Each globular cluster contains hundreds of thousands of stars. Most GCs are very old, around ~ 10 billion years old and were formed when the galaxy was being created. There are around one to two hundred GCs in our Milky Way galaxy, and a countless number in other galaxies, and studying these GCs gives us insight to the age of the galaxy and chemical composition of the initial gas cloud, or its metallicity. Since we know that RR Lyrae stars are extremely old, we can determine whether or not a GC is relatively young or old. A sighting of RR Lyrae stars inside a GC indicates that it must be ~ 10 billion years old or more.

M15 was the GC that I decided to conduct this search for RR Lyrae stars. The Catalog of Parameters for Milky Way Globular Clusters, or the Harris Catalog, contains various parameters—including distances, velocities, and metallicities for 157 known globular clusters in our Milky Way galaxy. I used this catalog to help select the GC I would investigate. I wanted a GC that was not too far away, less than 10.5 kiloparsecs (kpc). This filter was applied in order to avoid too much saturation and blending of stars and other properties make investigating a celestial object inconvenient. The next parameter that must be considered is the position (RA and DEC). This is because the CRTS has a limited range for its available light curves: RA ranges from 0h to 24 hours, Declination ranges from -70 to +70 degrees. The advantage of choosing this GC is that it's relatively small in size, ~ 175 light years in diameter, which allows for a faster and more concentrated search effort when looking for RR Lyrae stars. M15 is one of the oldest known globular clusters and there is some belief that an intermediate black hole may exist at its core. This implies that the RR Lyrae in M15 might be pushed to the edges of the globular cluster, giving us an area to focus on when performing the search.

3.2 Catalina Real-time Transient Survey

The Catalina Surveys, the first data release of its kind, involves two different surveys: the Catalina Sky Survey (CSS) and the Catalina Real-time Survey (CRTS). These surveys contain photometry, taken over a period of 7 years with the CSS Schmidt telescope, for ~ 198 million sources with apparent magnitudes between 12 and 20. The CSS focuses on searching for Near Earth Objects while the CRTS focuses on detecting stationary optical transients, such as RR Lyrae stars. Only the CRTS will be used in helping us find RR Lyrae stars. We begin by inputting an RA and DEC with a given radius (arcminutes) to search a circular region in the sky. All of the light curves for sources in that region are then extracted and available to download. The algorithm also involves correcting for the period for each of these light curves, but often fails in finding the correct period—which I’ll later discuss for how we correct the method. If a source has an apparent magnitude brighter than 12, the data received might be flawed due to high saturation but this is not an issue since the visual apparent magnitude for RR Lyrae in M15 is 15.83.

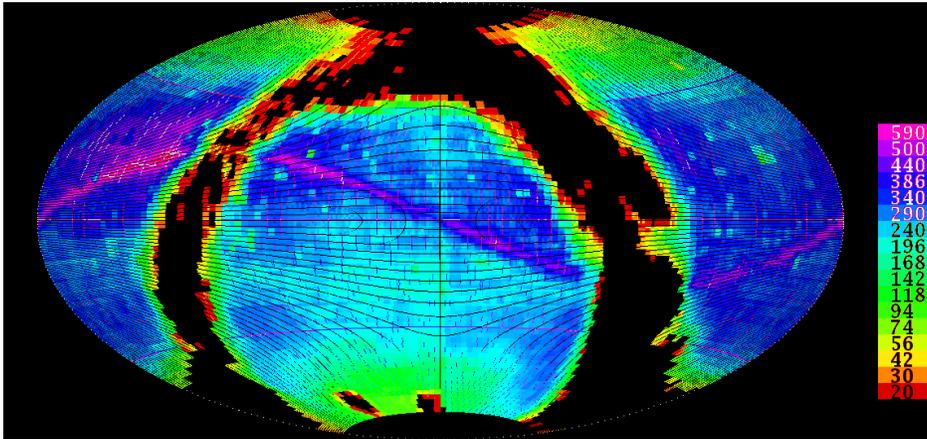


Figure 3: Shows the amount of galactic sky that is covered by the CRTS in equatorial coordinates. The color key indicates the amount of epochs that are located for each region.

3.3 The Sloan Digital Sky Survey

Another survey should take slight mention: The Sloan Digital Sky Survey (SDSS). The SDSS contains optical images of various celestial objects. There is an SDSS Navigation Tool that allows for easy navigation in the certain region of a given point on the sky. All that is required to enter is a RA and DEC to investigate. One can then navigate by clicking on the frame of the image or on random points in the image. A list of the selected object's parameters, or properties, along with an enlarged thumbnail image, is then outputted and available to experiment with. This becomes useful when searching for RR Lyrae stars since we can select any point in the displayed image and effectively use the point's RA and DEC to download its perspective light curve(s). We know that RR Lyrae stars should have a blue color, due to it's average temperature being between 6,200 and 7,000 Kelvin, which lets us eliminate most of the sources that appear any other color than blue. It's an extremely resourceful tool.

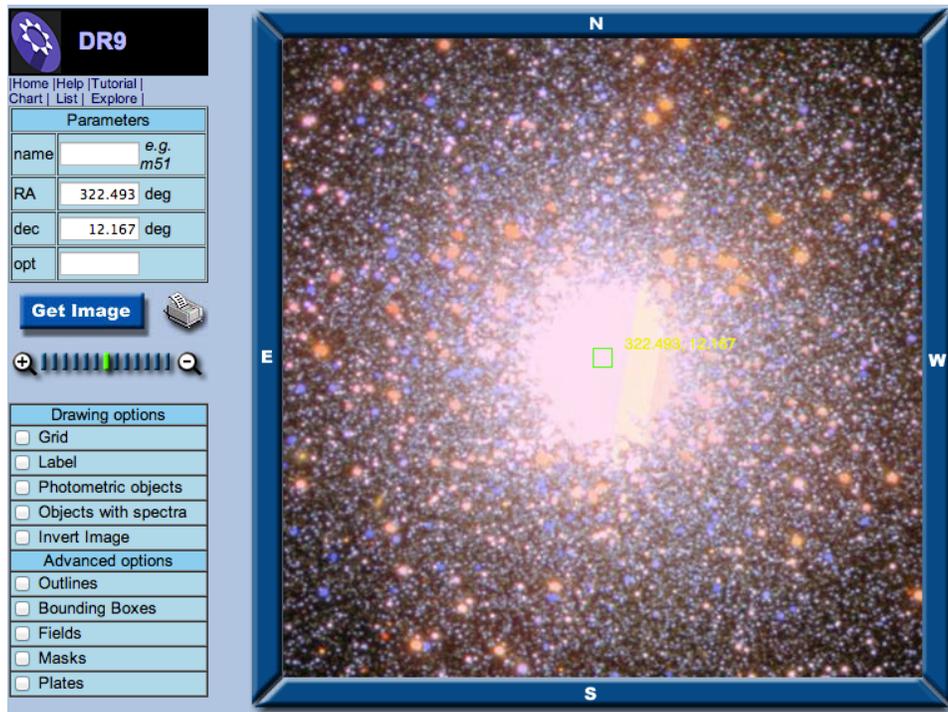


Figure 4: Optical view of M15 using the SDSS Navigation Tool along with various options that can be applied to the optical image

4 Calculations

4.1 Data Collection Method

The data release from the CRTS makes it very convenient when conducting the search since we don't have to execute CCD (Couple-Charged Device) observations to obtain the various light curves; they're already available to download. As mentioned before, once the several coordinates are outputted by the hexagonal tiling algorithm, each of those coordinates is then inputted into the CRTS website using its 'Single Region Search Service.' This feature creates a circle of a default radius (predetermined to be 1.5 arcminutes) with the given position (RA and DEC) as the center. The website then goes through the Photometry Catalog Database (Photcat DB) and queries the region for all available sources and their respective light curves.

Several thresholds, or filters, are then applied to various parameters in order to only retrieve the potential RR Lyrae candidates. The query has the following parameters outputted for each source found: RA, DEC, number of epochs (points), Catalina ID, period, and the False Alarm Probability (FAP). The visual apparent magnitude level of the horizontal branch (RR Lyrae stars) for the globular cluster M15 is known to be 15.83. Therefore, the range of apparent magnitudes that I search for will be 15.83 ± 1.5 . The range of an entire magnitude makes sure that I don't miss any potential sources in my search. The distance modulus is calculated from knowing the average absolute magnitude for an RR Lyrae ($\sim .5$) and the distance to M15 (~ 10.4 kpc):

$$\mu = 5 \log_{10}(d) - 5 \tag{4}$$

where μ is the difference between the apparent magnitude, m , and the absolute magnitude, M . The FAP tells us how likely the period found is incorrect. RR Lyrae sources found on the website are known to have extremely small FAPs, ideally below 10^{-8} , which I use to establish that threshold.

Once all the potential sources have been found for a region, the light curves are then downloaded for each source and all of its corresponding epochs. The data is then conditioned: The file produced by the CRTS website is a comma separated variable file. We convert this to a space separated file with no text headers. Finally, the .cvs extension is changed to .dat in order

for the period correcting algorithm to run properly. We then proceed with analyzing our new data.

4.1.1 Lafler-Kinman Algorithm

Time series analysis is used to search for periodicities occurring in a process in time. In our case, a time series analysis searches for hidden periods and reconstructs phase process diagrams from photometric observations. The Lafler-Kinman method starts out by taking some light curve that has magnitude vs time containing unevenly sampled time series. It assumes that the true signal is buried within this series and that it is continuous. The data is then phased by picking some trial period, P , and then folding it. Folding involves splitting up the time into P bins and then overlaying each bin created. We then normalize the phase to have it run from zero to one. Now, if a true periodicity exists in the data, then at correct period, P^* , the sum of the squared distance between adjacent points in the phased light curve will be minimized. Essentially, multiple P are calculated, you keep track of the lowest value, and the minimum squared distance will give you the correct P . This is displayed mathematically by taking a time series of data, $x_i = x(t_i)$, and then appropriately creating a phase series $\tilde{x}_j = \tilde{x}(\phi_j)$ where ϕ_j is the ordered phase calculated for a period and is given by the following:

$$\phi_j = \frac{\text{mod}(t_i, P)}{P} \quad (5)$$

which basically displays the new time for our phased data. So then, the Lafler-Kinman statistic, which is something used to determine the likelihood of an event happening, is as follows:

$$\theta(P) = \sum_j^n (\tilde{x}_j - \tilde{x}_{j+1})^2 \quad (6)$$

where it is assumed, for each phase, that $\tilde{x}_{n+1} = \tilde{x}_1$. For the correct period, P^* , $\theta(P^*)$ will be a minimum. Even though $\theta(P)$ seems to be normally distributed over small ranges of P about some mean value, this mean value will vary over long ranges of P . So, a signal with a true period will contain a strong minima position at harmonics and sub-harmonics of P^* . These are measured from the local mean value of $\theta(P)$. A running median is needed to attain a smooth curve; We “flatten” the spectrum by using this running median for short stretches of P , and then computing the following statistic

which displays the spectrum with peaks at P^* along with its harmonics and sub-harmonics:

$$\tilde{\theta}(P) = \langle \theta(P) \rangle - \theta(P) \quad (7)$$

where $\langle \theta(P) \rangle$ is the running median. $\tilde{\theta}$ can now be normalized by computing its standard deviation over the entire range of sample to evaluate a final statistic:

$$\theta'(P) = \frac{\tilde{\theta}}{\sigma} \quad (8)$$

where σ is the standard deviation of $\tilde{\theta}(P)$. We can effectively use this statistic to calculate the false alarm probability (FAP) by testing several periods and multiplying that number by the error function.

4.2 Data Analysis

The first part of the algorithm (Dr. Matthew Benacquista, private communication) filters out all sources that don't fall within a magnitude and a half of the visual apparent magnitude level. The remaining sources are then cleaned from outliers by removing any points that are at least 4 standard deviations away from the average magnitude. The error bars are sometimes bigger than the variations in the light curve when it finds a period which, in turn, could give a very small value for the FAP. So, the next part takes the files and cleans anything with a flat line. Finally, the code checks for the correct period by applying the Lafler-Kinman algorithm, which is explained in detail in the previous section. If the FAP is less than 10^{-8} , it passes the filter and is outputted to a file containing all the periods. Several scripts were made in making the data analysis more efficient; these will be discussed in the following section.

4.3 Issues Encountered

The extraction of photometry from the CRTS website proved to be time consuming. We had to download all the light curves for each individual coordinate (RA and DEC) with the search region having a radius of 1.5 arcminutes—once again, in order to avoid exceeding the maximum number of sources that can be displayed at once. When changing the total area to be searched to encompass M15's tidal radius, the number of coordinates for which we needed to download light curves went from 19 to 331. An algorithm was created, in Python, by one of the CRTS developers in order to solve this

dilemma (Dr. Matthew Graham, private communication). The code reads a file that contains all of the coordinates (RA and DEC) and then simply extracts all the light curves simultaneously, saving an exorbitant amount of time.

In choosing a radius for each coordinate, I had originally arrived at 1.8 arcminutes using the previously mentioned method in the Introduction. Unfortunately, upon inputting a coordinate, some of the circles had exceeded the maximum number of objects that could be displayed. I then reverted to a radius of 1.5 arcminutes, and no further issues ensued in regards to this problem. This, of course, meant that several new coordinates were added or replaced; but this also meant a thorough search was being executed.

In performing the data analysis, several parts of the code, as mentioned before, were individually executed. This eventually proved to be tedious, especially when considering the fact that multiple GCs were still going to be searched. I created a script, in Bash, in order to solve this issue. When the script is run, it only asks for two arguments: the name of the input file—the one containing all the downloaded light curves from the CRTS website—and the visual apparent magnitude. The following displays the code at work:

```
1 #!/usr/bin/bash
2 []
3 src=/Users/khalidkayal/Documents/rrlyrae/F0R_SCRIPTS
4 localdir='pwd'
5
6 #Check to see if inifile.dat is in the directory, if not exit.
7 if [ ! -e inifile.dat ]
8 then
9     echo "inifile.dat doesn't exist, it will be copied over"
10    cp $src/inifile.dat .
11 fi
12
13 #Run the first part: Light curve seperator
14 $src/LightCurveSeparator
15 ls 11*.dat > list.dat
16 ls 31*.dat >> list.dat
17
18 #Run second part: Clean outliers
19 $src/OutlierCleaner
20 ls c1*.dat > list.dat
21
22 #Run third part: Flat Line Cleaner
23 $src/FlatLineCleaner
24 ls f1*.dat > input.dat
25
26 #Last Part: Find the Period
27 $src/LK_PeriodFinder
28
29
```

Figure 5: Algorithm written in bash

Once all the light curves were generated by the period-correcting algorithm, we had to individually plot each file, inputting arguments like the title, axis, etc. This was very inconvenient since there existed a lot of files that needed to be plotted—again, it wouldn’t be efficient when conducting searches on other globular clusters. Another script was then created, in Python, that plots all of the files in a user-created file, and saves them to a directory named ‘plots.’ Each plot also displays its unique Catalina ID as the title and saves the file under that ID as well. Now, with all the issues solved, we were able to efficiently search for RR Lyrae stars in M15.

5 Results

The algorithm returned 82 liable candidates to evaluate. After various literature searches and sifting, the following RR Lyrae stars were recovered.

| Catalina ID | RA | DEC | Mag | P (days) | FAP |
|---------------|----------|---------|-------|------------|------------------------|
| 1112113020943 | 322.3560 | 11.8475 | 16.62 | 0.3227 | 3.92×10^{-15} |
| 1112113023771 | 322.3988 | 11.9210 | 17.20 | 0.4709 | 5.56×10^{-28} |
| 1112113026440 | 322.4511 | 11.9887 | 15.62 | 0.4143 | 1.20×10^{-27} |
| 1112113035357 | 322.4439 | 12.1688 | 15.08 | 0.6843 | 1.69×10^{-22} |
| 1112113035399 | 322.5146 | 12.1956 | 15.14 | 0.3677 | 6.05×10^{-10} |
| 1112113035453 | 322.5412 | 12.1616 | 15.31 | 0.3433 | 4.17×10^{-21} |
| 1112113035482 | 322.5787 | 12.1650 | 15.55 | 0.6653 | 3.74×10^{-37} |
| 1112113035510 | 322.5038 | 12.2137 | 14.94 | 0.6552 | 6.49×10^{-9} |
| 1112113035512 | 322.4605 | 12.1219 | 15.25 | 0.6272 | 1.95×10^{-17} |
| 1112113035539 | 322.4458 | 12.1869 | 15.28 | 0.4716 | 1.67×10^{-9} |
| 1112113035642 | 322.5477 | 12.1616 | 15.35 | 0.5757 | 1.53×10^{-26} |
| 1112113035736 | 322.4219 | 12.0908 | 15.65 | 0.3682 | 0 |
| 1112113035766 | 322.4197 | 12.2077 | 15.21 | 0.9983 | 1.51×10^{-10} |
| 1112113036426 | 322.3988 | 12.1539 | 15.43 | 0.7202 | 0 |
| 1112113036972 | 322.5468 | 12.2390 | 15.27 | 0.6327 | 4.23×10^{-32} |
| 1112113040319 | 322.5797 | 12.3165 | 15.61 | 0.6707 | 0 |
| 1112113040571 | 322.4623 | 12.3175 | 15.66 | 0.4003 | 0 |

Table 1: Parameters of recovered RR Lyrae stars in M15

6 Conclusions

RR Lyrae stars hold a tremendous amount of potential in the field of Astronomy because their intrinsic properties can be determined by stellar pulsation theory and stellar evolution. Because of this, they are ideal stars for comparing the results of these theoretical approaches. We completed a tidal search of the globular cluster M15. After searching through over 4,000 sources in the sky, only 82 sources made it past the cleaning. Out of those 82 candidates, 24 were recovered as celestial objects in the sky. Of these 24, we were able to successfully identify 17 as RR Lyrae variable stars. One of the 24 objects, believed to be an eclipsing binary system, was found in the search but has yet to be identified in a literature search. A plot of this object is found in Appendix C. This project started off using traditional methods of obtaining and sifting through the data until the previously mentioned algorithms were developed. Since the addition of the algorithm, we are now able to efficiently search multiple globular clusters with minimal time. Our next step would be to continue with an in-depth search of several globular clusters in our Milky Way galaxy, and hopefully find new RR Lyrae variables in order to gain a better understanding of these exotic stars.

7 Acknowledgments

I want to thank the ARCC Executive Committee members for all their support and valuable time spent in guiding me throughout the development my thesis. I also would like to thank fellow ARCC members of the ARCC program at the University of Texas at Brownsville (UTB) for helping me understand certain terms and concepts. I'd also like to acknowledge my loving mother for the everlasting support she was constantly providing me with. Finally, I would like to thank and acknowledge my mentor Dr. Matthew Benacquista for his support, wisdom, patience and guidance in providing me with the appropriate skill set to engage in and continue this research.

8 Appendix

8.1 A: The Blazhko Effect

Several RR Lyrae experience what is known as the Blazhko effect; these RR Lyrae stars are then considered Blazhko variables, which indicates that their pulsations are characterized by periodic modulation of the amplitude—with a periodicity of around 30 days—and phase of maximum light. Interestingly enough, the RR Lyrae star is the brightest known Blazhko variable. The light curves of an RR Lyrae star that is undergoing the Blazhko effect change significantly from plot to plot on a short timescale. When RR Lyrae stars display the Blazhko effect, the difference in brightness at maximum light is more pronounced than when its at minimum. The Blazhko effect is mainly displayed among very short-period RRab stars. Also, it reduces, rather than extends, the original height of the maximum on a light curve.

Even though Blazhko variables are quite common, the mechanism that produces their amplitude/phase modulations is still not very well understood. It is thought that RRb stars are formed as a result of the Blazhko effect; but this has yet to be verified. The two current and most accepted theories are: that the Blazhko effect is a result of some sort of mixing of pulsational—radial—modes OR that the Blazhko effect is related to the magnetic cycles in the stars (Detre and Szeidl 1973) [5]. The theory that seems most promising is that the Blazhko effect is a consequence of modal interference, since it slightly accounts for the changing period distributions of RR Lyrae stars in globular clusters. It's still, however, unable to fully entail the behavior of the Blazhko phenomenon.

8.2 B: RR Lyrae Light Curves Recovered

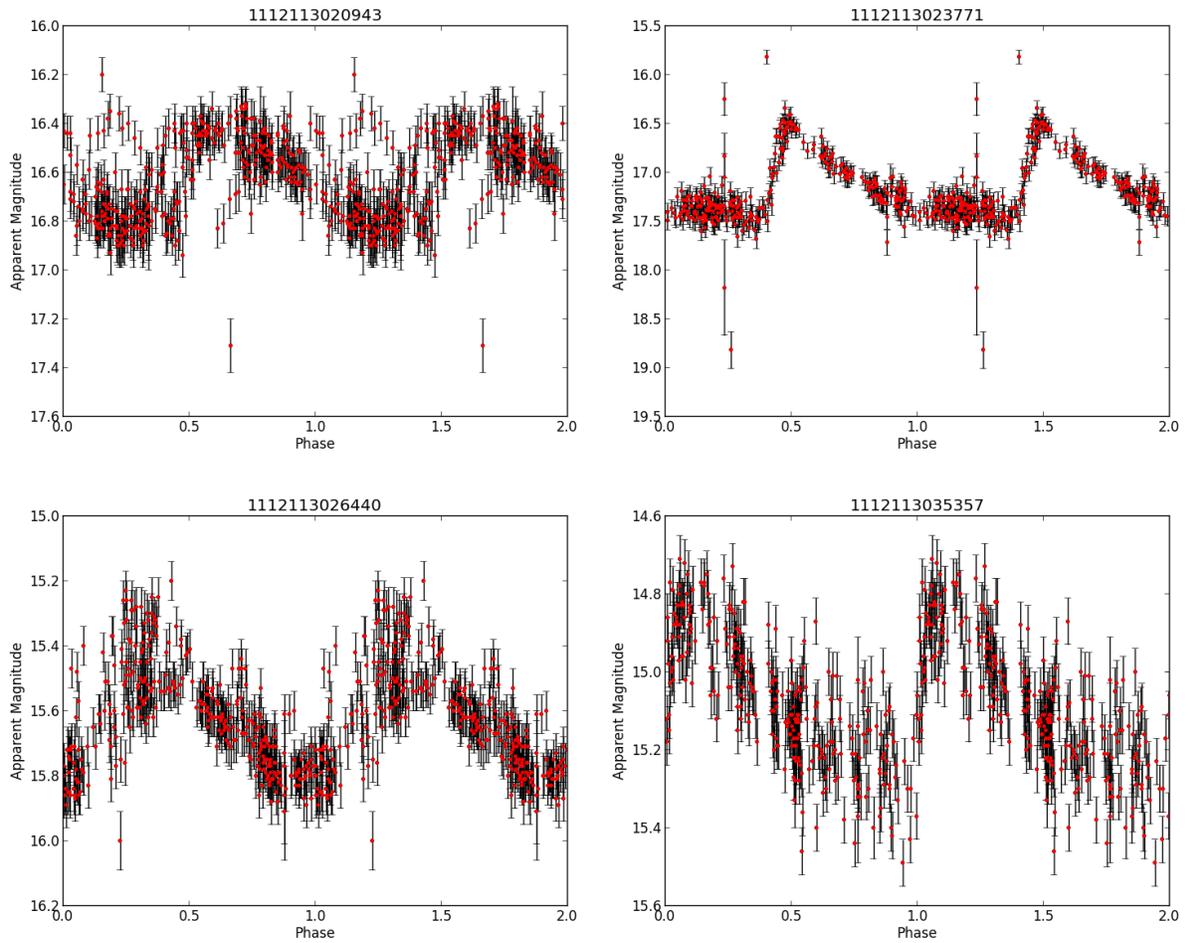


Figure 6: Light Curves Recovered. The points, or epochs, are represented in red and the error bars are shown by the black lines.

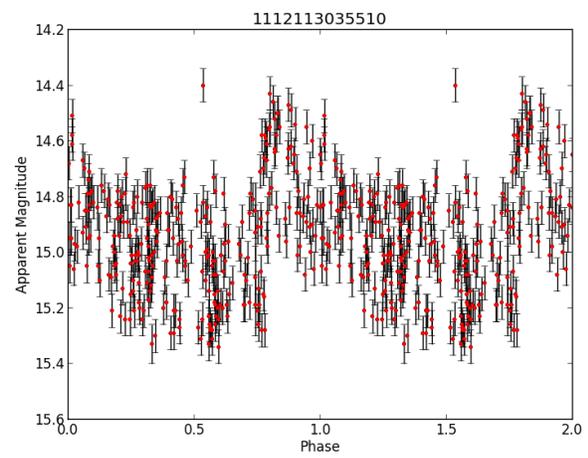
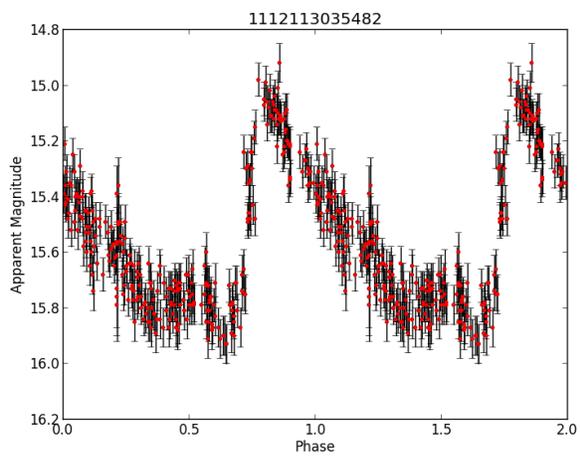
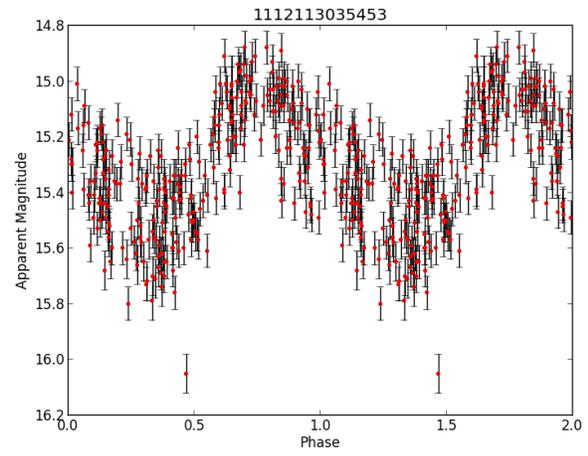
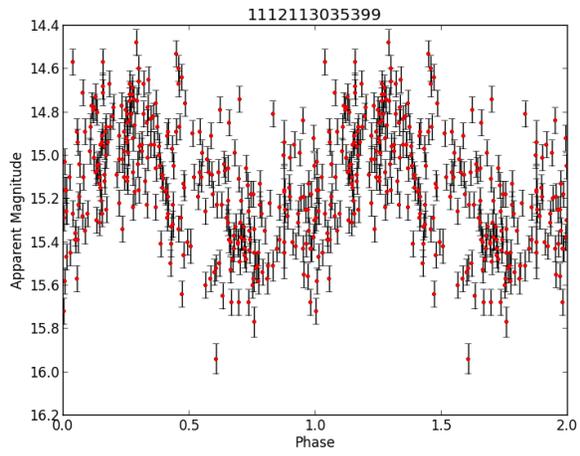


Figure 7: Light Curves Recovered (cont.)

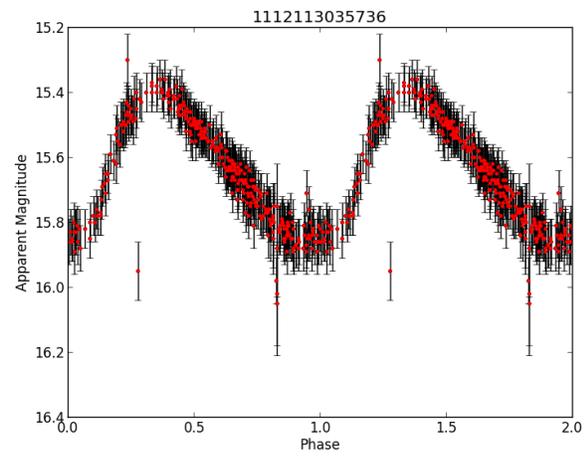
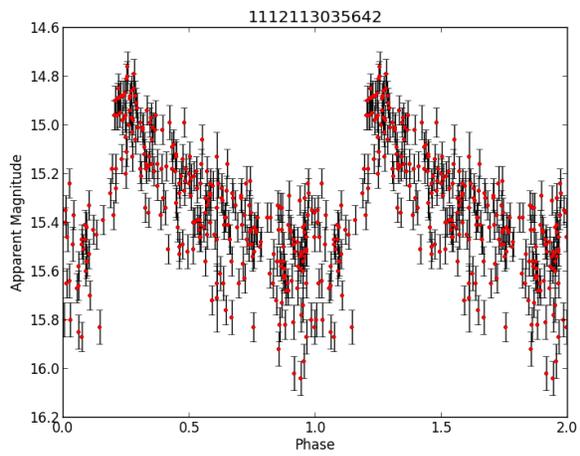
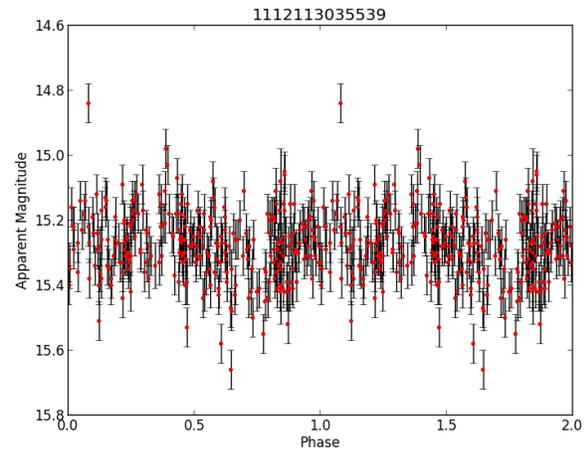
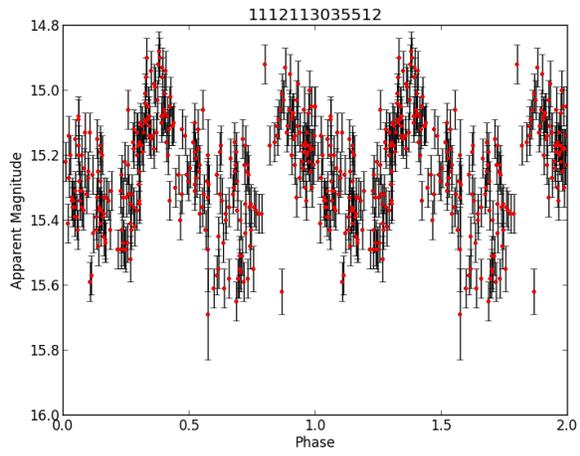


Figure 8: Light Curves Recovered (cont.)

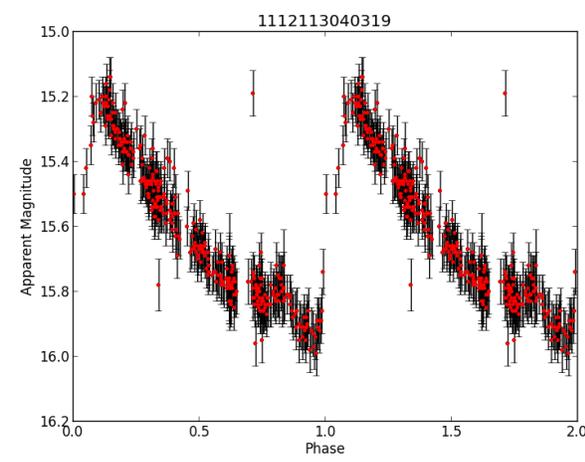
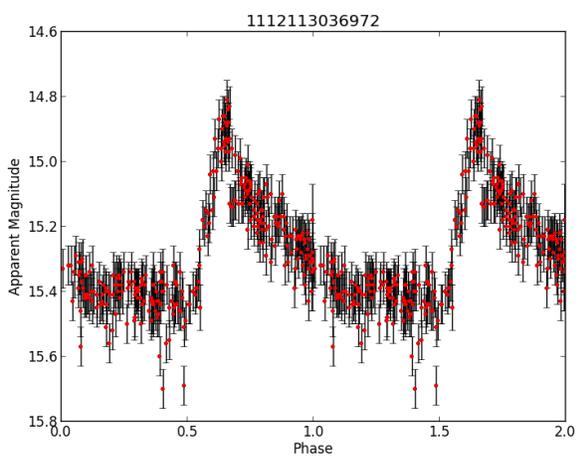
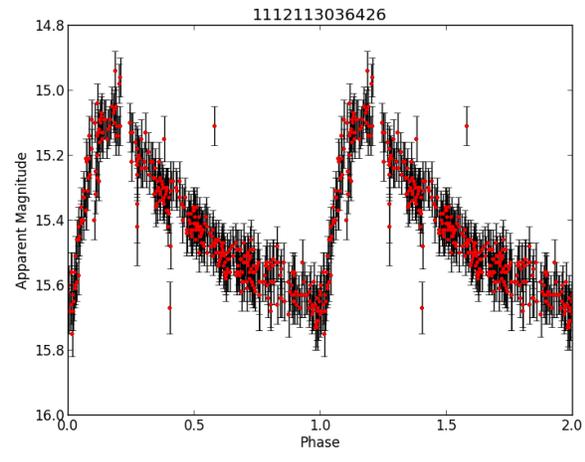
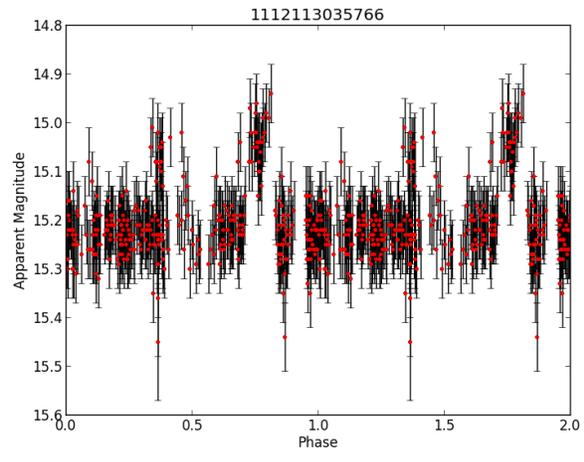


Figure 9: Light Curves Recovered (cont.)

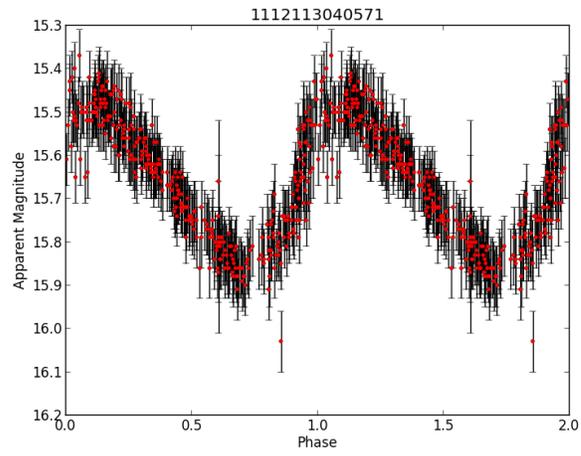


Figure 10: Light Curves Recovered (cont.)

8.3 C: Light Curve of a Celestial Object

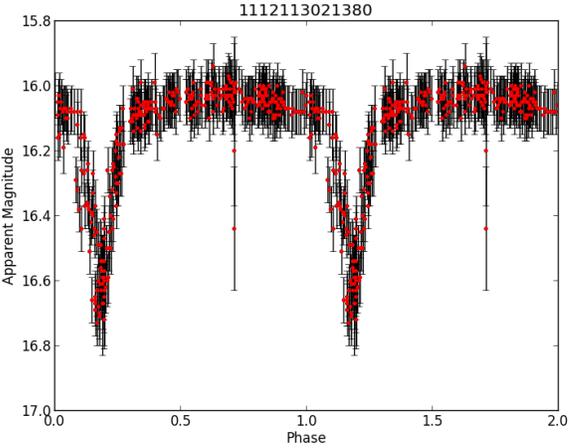


Figure 11: Light curve recovered that is believed to be an eclipsing binary system.

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