

Standardizing Light Curves of RR Lyraes in the Globular Cluster NGC 5466

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ABSTRACT

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Variable stars, like RR Lyraes, can be useful for determining globular cluster characteristics. The globular cluster NGC 5466 has many RR Lyraes in a relatively spacious field. The RR Lyraes in the globular cluster NGC 5466 were used to create light curves from data taken using photometry at West Mountain Observatory in Utah. This photometric data is input into a computer program called FITLC, which determines periods and amplitudes by fitting light curve templates to the data. These periods are compared with the periods found in Ferro *et al.* (2008). Metallicity of the cluster is solved for using three different methods outlined in Jeffery *et al.* (2011) that also depend on period: the Sarajendini, Alcock, and Bono method. The Alcock method provided metallicity results closest to Ferro *et al.* (2008) with the average metallicity of $[Fe/H] = -2.127437$ and a standard deviation of 0.062176.

Keywords: [RR Lyrae, NGC 5466, globular cluster, photometry, light curve, period, metallicity]

Contents

Table of Contents	iii
List of Figures	iv
List of Tables	iv
1 Introduction	1
1.1 Globular Clusters	1
1.2 Variable Stars	3
1.3 RR Lyrae Characteristics	3
1.4 Past Work	5
1.5 Overview	6
2 Methods	7
2.1 Photometry	7
2.2 Fit Light Curve	10
2.3 Determining Metallicity	11
3 Results	13
3.1 Light Curves and Periods	13
3.2 Metallicity Results	13
3.3 Period Comparison with Ferro <i>et al.</i> (2008)	15
3.4 Conclusion	17
Bibliography	18
Index	19

List of Figures

1.1	NGC 5466	2
1.2	RRab and RRc-like lightcurves	4
2.1	Johnson-Cousins Filters	8
2.2	NGC 5466	9
3.1	Light Curves and Periods for the NGC 5466 RR Lyraes	14
3.2	Metallicity Histograms	15

List of Tables

2.1	Standard Star V Magnitudes	10
3.1	Period Comparison	16

Chapter 1

Introduction

1.1 Globular Clusters

Globular clusters are large, gravitationally bound stellar clusters that form from collapsing molecular clouds. Since the stars in the cluster form from the same cloud, they are roughly the same distance from Earth, as the distance between stars in the cluster is small compared to the distance of the cluster from Earth. Forming from the same cloud also means that the composition of the stars are similar, and globular clusters are usually metal poor. The stars in a globular cluster form at roughly the same time, giving about them the same age. The differences between stars in a globular cluster results from varying initial masses, which makes globular clusters excellent environments for studying stellar evolution (Percy 2007). The globular cluster I am studying is called NGC 5466. NGC stands for New General Catalog, and this is object 5466. It is located in the constellation Bootes. Figure 1.1 shows an image of NGC 5466.



Figure 1.1 A picture of NGC 5466 taken at West Mountain Observatory. North is pointing to the bottom of the picture and East is pointing to the right.

1.2 Variable Stars

Variable stars, or variables, are stars whose apparent brightness periodically change. An extrinsic variable is a star whose brightness changes due to a geometric process, such as an eclipse. An intrinsic variable star is a star which varies brightness due to a physical change. A common physical change is caused by the star pulsing, i.e., changing its radius. The change in brightness of these stars can be plotted over time and displayed as a light curve. The change in radius is usually caused by the instability between the outward pressure of the star and the inward gravitational force trying to collapse it. For this reason, variable stars can be found on the Hertzsprung-Russell (H-R) Diagram—a chart that plots the luminosity of a star against its temperature—in a region named the instability strip.

One classification of variable stars is the RR Lyrae, which are radially pulsating A-F stars. These variable stars have amplitudes ranging from 0.2 mags to 2 mags in the V filter and periods ranging from a few hours to a day (Good 2003). The name for the class comes from a popular variable star labelled RR found in the Lyra constellation, hence RR Lyrae. Two common types of RR Lyrae stars are RRab and RRc stars. RRab stars have a rapid increase in brightness followed by a slightly slower decrease in light. RRab stars usually have periods between 0.3 and 0.9 days. RRc stars are always changing in brightness, so their pulsations are more consistent, and their periods usually range between 0.1 and 0.5 days. The light curves produced by these stars can either resemble a sawtooth plot or a sinusoid. A sawtooth light curve indicates an RRab star, while a sinusoid light curve indicates an RRc as seen in Figure 1.2. RR Lyrae variable stars will be the focus of this thesis.

1.3 RR Lyrae Characteristics

RR Lyraes are known to have around the same luminosity. The apparent brightness, or magnitude, of a star is how bright the star looks to an observer on Earth. Absolute brightness is defined as the

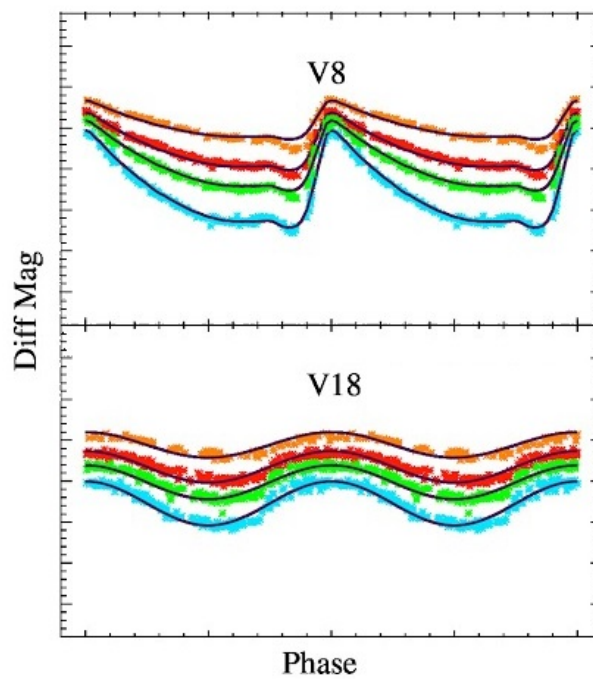


Figure 1.2 The top curve shows the shape of the light curves for RRab stars, and the bottom light curve is for RRC. The x-axis is time, and the y-axis is apparent magnitude in the different filters. These curves are for V8 and V18 in NGC 5466

apparent magnitude of a star if the star was 10 parsecs away (32.6 light years), while luminosity is the power output of the star. Astronomers use luminosity and absolute brightness interchangeably. Both apparent and absolute brightness are measured in magnitudes (Percy 2007). A lower magnitude means a brighter star.

The time it takes an RR Lyrae to cycle through a complete pulse, its period, is related to its luminosity. Astronomers can use photometry, measuring the light output of a star, to plot a light curve of an RR Lyrae and find its period. This period can be used to find characteristics of the star, such as metallicity.

Stars are mainly composed of 75% hydrogen and 23% helium and the other elements found in the stars are referred to as metals. Stars can be organized into two categories when referring to their composition: Population I or II. Population I stars are metal rich, like the Sun, and Population II stars are metal poor. RR Lyraes in globular clusters are usually population II. Knowing how much metal is in a star, or the metallicity of the star, can help when developing stellar evolution theories, which is why finding the metallicity of RR Lyraes in a globular cluster is important. Astronomers quantify metallicity as the ratio of iron atoms to hydrogen atoms in a star compared to the same ratio in the sun. This ratio is defined as $[Fe/H]$. Usually metallicity is found by studying a star's spectrum, but methods do exist to find metallicity using photometry. I outline such three metallicity relations in Chapter 2.

1.4 Past Work

The periods I find for the RR Lyraes in the globular cluster NGC 5466 are compared to the periods found by Ferro *et al.*(2008). The standard stars used in Ferro are the same that will be used by me when standardizing the light curves. The past work of Jeffery *et al.*(2011) on RR Lyraes in M31 is used to help determine the metallicities of the RR Lyraes in NGC 5466. Jeffery *et al.*(2011)

references three different methods to determine metallicity: the methods of Alcock *et al.*(2000), Bono *et al.*(2007), and Sarajendini *et al.*(2008), which are discussed in Chapter 2. These three results are compared with the metallicity values found by Ferro *et al.* (2008) of the objects to determine which method works best for this cluster. These three methods use RRab light curves, but Jeffery also mentions a method that works for RRC light curves, although it is not used in this thesis. Standardizing the magnitude of RR Lyrae variable stars is necessary to determine an accurate light curve.

1.5 Overview

Standardizing the light curves for the RR Lyraes in NGC 5466 helps determine the metallicity of the cluster. I use the light curves I create to determine the most likely periods for each variable star. The period-luminosity relation can then be applied with the estimated period to find the absolute magnitude. According to current creation theories, we can assume that metallicity, and other characteristics of a star in a cluster also apply to the other objects in that cluster. These methods used are detailed in Chapter 2. Therefore, once I find the metallicity of the RR Lyraes, I know the metallicity of NGC 5466. These values are compared with the values for NGC 5466 determined by Ferro *et al.* (2008) in Chapter 3.

Chapter 2

Methods

2.1 Photometry

Light curve photometry is the measuring of brightness variations over time. This data is presented as a plot. This is extremely useful for variable stars—such as RR Lyraes—because their light curves contain useful information. For this thesis, the period of the light curve is important for determining several attributes of the RR Lyraes and thus NGC 5466. In fact, Warner (2006) argues that RR Lyrae type variable stars are the most important stars to understand because of their correlation between period and luminosity. For this reason, RR Lyraes are an important tool for understanding globular clusters like NGC 5466.

To create a light curve, data must be extracted from the images in different filters capturing the globular cluster. The filter system used to capture NGC 5466 is the Johnson-Cousins standard. This filtering system was created by H.L. Johnson and W.W. Morgan in the 1950s (Warner 2006). It has evolved into the most commonly used filter system for most astronomers. The filters used to photograph NGC 5466 for this thesis were the B, V, R, and I filters. The function of different filters is to determine which frequencies of light are most prominent in the star. Figure 2.1, taken from the

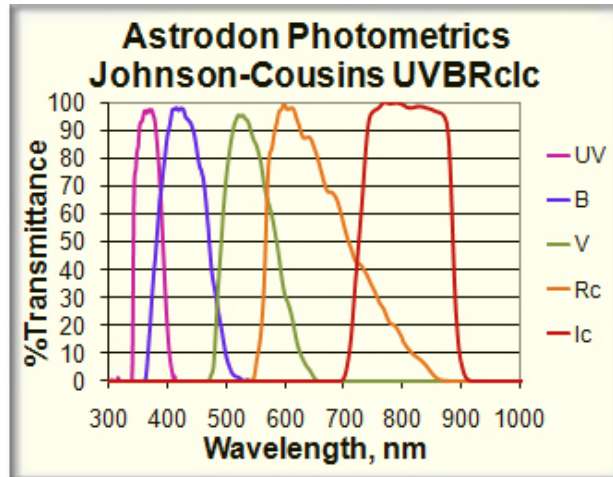


Figure 2.1 The Johnson-Cousins filter transmission curves. Light wavelength is given in nanometers. From Astrodon Photometrics (<https://astrodon.com/products/astrodon-photometrics-uvbri-filters/>)

Astrodon Photometrics website, shows the wavelengths of light each filter allows to pass through. The V filter is utilized when determining the metallicity of the RR Lyraes using the methods outlined in Jeffery *et al.* (2011).

Standard stars are needed to calibrate the brightness of the stars around them. The standard stars in globular cluster NGC 5466 are stars with known V magnitudes (mags). They are labeled in Figure 2.2, taken from Ferro *et al.* using single letters. The RR Lyraes in NGC 5466 are the target stars and are labelled with a capital V followed by a number. Take note of the correction made to the location of V7. Table 2.1 lists the magnitude found for each of the standard stars where the n values are the number of photos used by Ferro *et al.* (2008) to determine the magnitude.

The three sets of data, occurring in 2014, 2015, and 2016, were obtained at West Mountain Observatory (WMO) in Utah. The images were taken using a 0.9 meter telescope operating at $f/5.5$ using a PL3041 CCD. The PL3041 CCD is 2K x 2K array with 15 micron pixels. The plate scale is 0.61 $\ddot{\text{r}}/\text{pixel}$ with this CCD giving a square fov that is 21' on a side. The B, V, and R filters were used for all three years, and the I filter was used only in 2016. The reductions done on the data were completed by Dr. Joner from Brigham Young University (BYU), using IRAF scripts to

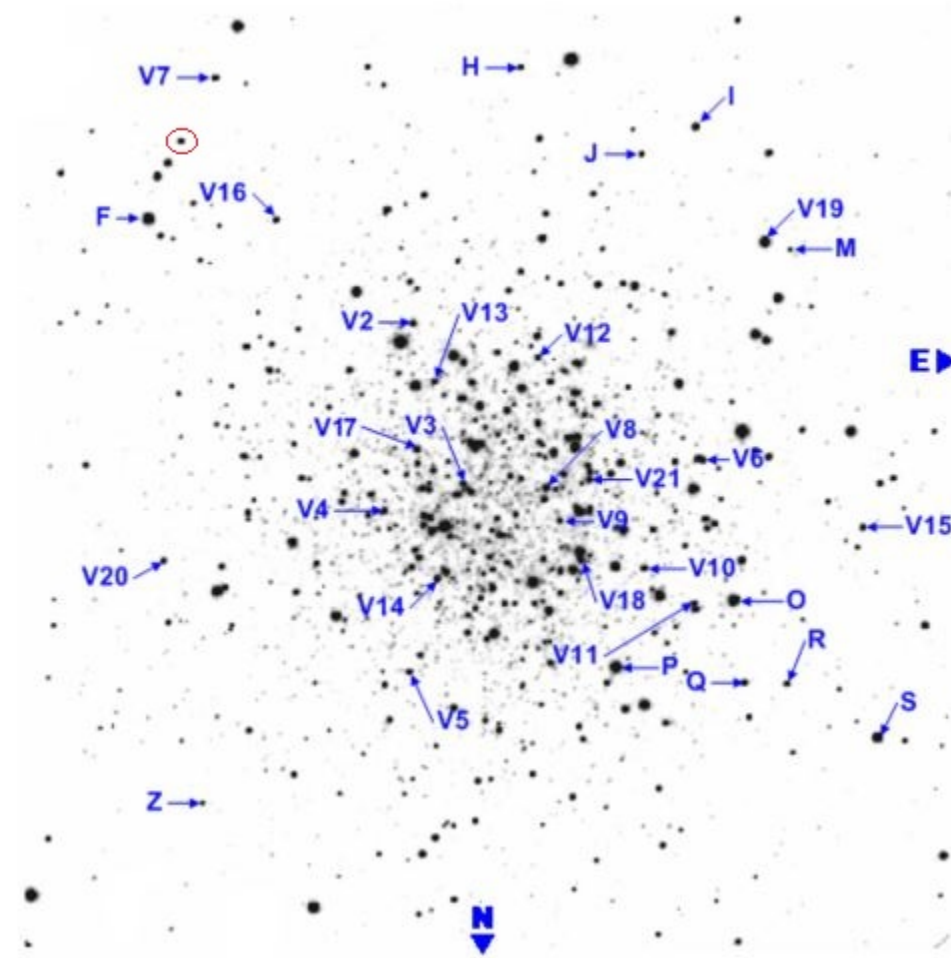


Figure 2.2 A picture on NGC 5466, with the standard stars and variable stars labelled, taken from (Ferro et al. 2008). A correction for V7 has been made, and the correct V7 star is circled in red.

Table 2.1 Standard V magnitudes for the standard stars. The star labels correspond with the stars in Figure ???. The letter n corresponds with the number of images used to calculate the standard magnitude (Ferro et al. 2008).

Star	V (mags)	n
F	14.11	24
H	16.66	41
I	15.78	42
J	16.87	44
M	17.64	41
O	14.28	44
P	14.13	43
Q	16.37	44
R	16.67	43
S	14.88	43
Z	17.57	43

Overscan, Bias, Dark, and Flat correct the images before they were analyzed. I used the reduced images with the DAOPhot program to determine the apparent brightness of the star . DAOPhot used aperture photometry to count the number of photons in each pixel of the star and subtract the background brightness to give an accurate reading of the apparent brightness. The data files, .mag files, produced by DAOPhot are used to construct the RR Lyrae light curves.

2.2 Fit Light Curve

Fit Light Curve (FITLC) is a program designed by a Sarjendini *et al.*(2009) that analyzes the standard photometry files from DAOPhot to create light curves for each star. To use the program, I insert a range to find the variable star's period, starting with one decimal place. FITLC fits the best known light curve shapes to the data from 10 known light curve templates using a chi square best fit, and determines a period that has one more decimal place than the range I provided to the program. Then I repeat the process now using a range that has the same amount of decimal places as the last

period found, until I get the best fit to the light curve. The best fit usually provides periods to the sixth decimal place.

2.3 Determining Metallicity

Jeffery *et al.* (2011) outlines three methods to finding metallicity of RRab—RR Lyraes with sawtooth light curves. Metallicity is quantified by the ratio denoted by $[Fe/H]$ discussed in Chapter 1. The first method I use to obtain $[Fe/H]$ was derived by Sarajedini *et al.* (2006). This relation was determined by fitting data for 132 RR Lyraes in the solar neighborhood. The data was taken by A.C. Layden (Jeffery *et al.* 2011). The equation found expressing the relationship is

$$[Fe/H] = -3.43 - 7.82 \log P_{ab},$$

where P_{ab} is the period of the RRab star in days. This relation works for RR Lyraes with metallicities between -2.5 and 0.0. This relationship only requires the RR Lyraes period to determine metallicity.

The next relationship was found by Alcock *et al.* (2000). The equation is

$$[Fe/H]_{RRab} = -8.85[\log P_{ab} + 0.15A(V)] - 2.60,$$

where $A(V)$ is the amplitude of the light curve in the V filter. The Alcock method is one of the most frequently used metallicity relationships and it depends on both the amplitude of the light curve and the period of the RR Lyrae.

The last relationship explored was discovered by Bono *et al.* (2007). The three equations used are

$$k(1.5)_{puls} = 0.136 - \log_{10} P_{ab} - 0.189A(V)$$

$$M_V^{k(1.5)} = 0.12 + 2.65k(1.5)_{puls}$$

$$M_V^{k(1.5)} = 1.19(\pm 0.10) + 0.50[Fe/H] + 0.09[Fe/H]^2,$$

where $k(1.5)_{puls}$ is a parameter dependent on P_{ab} and amplitude, $A(V)$, of the RRab stars to find their absolute magnitude, M_V , which then leads to the metallicity of the star, $[Fe/H]$. I used the data recovered from the NGC 5466 RR Lyraes over all three years to determine the metallicity of the cluster using these three methods.

Chapter 3

Results

3.1 Light Curves and Periods

The RR Lyrae light curves and periods were obtained using Fit LC, which is discussed in Chapter 2. The FITLC light curves obtained for the RR Lyraes in NGC 5466 are displayed in Figure 3.1. FITLC used a range of data from 2014 to 2016, with some exceptions noted in the figure description. The best determined period for each variable star is included in days. A period given in days is included for each variable star. These periods are compared with the periods reported by Ferro *et al.* in Section 3.4 (Ferro et al. 2008). The light curves display both RRab and RRC stars. If you remember back in Section 1, RRab light curves are sawtooth shaped, while RRC look more like a sinusoid. The metallicity relations given by Jeffery *et al.* will be used on the RRab stars (Jeffery et al. 2011).

3.2 Metallicity Results

The RR Lyrae periods were used together with the Alcock, Bono, and Sarajendini methods to achieve metallicity results. These methods are detailed in Chapter 2. Histograms were made for

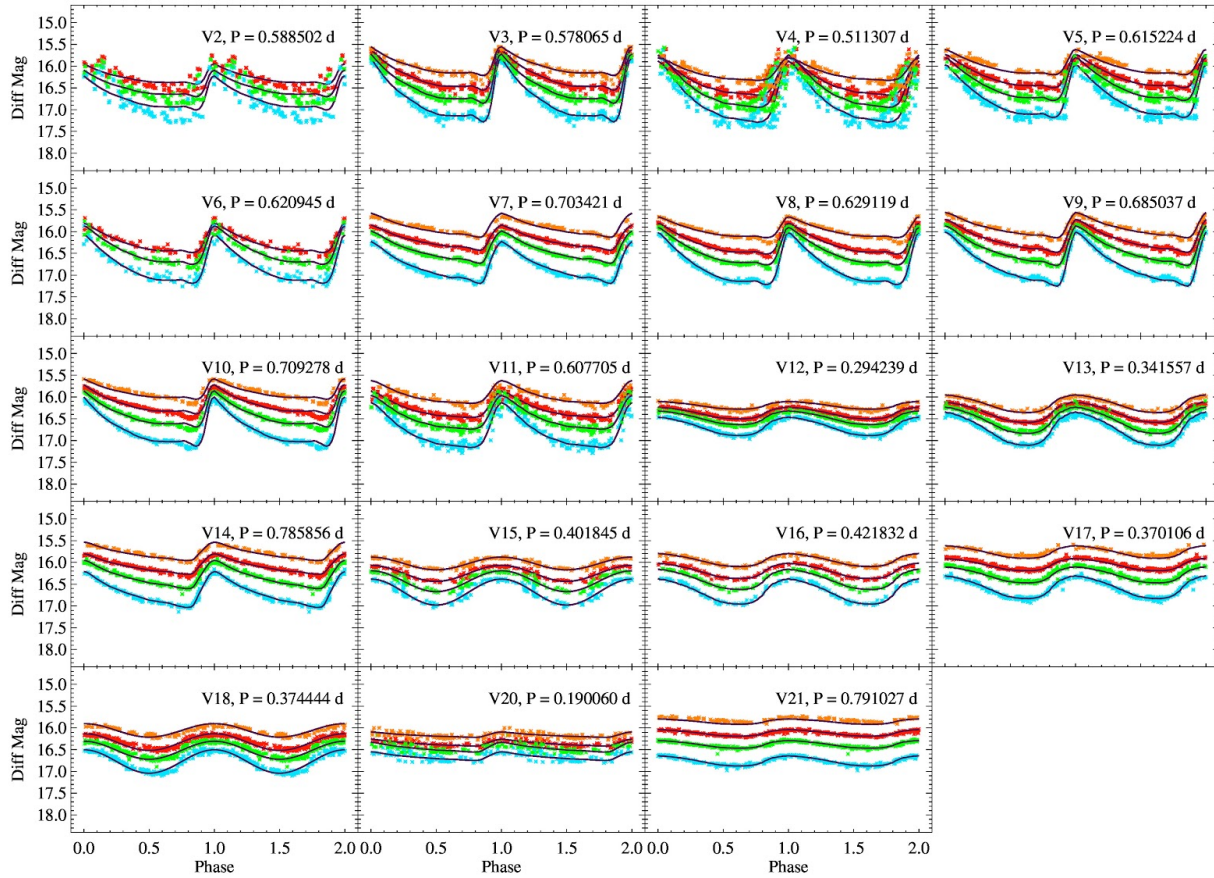


Figure 3.1 Light curves and periods found for the RR Lyraes in NGC 5466. The light curves display the B (blue), V (green), R (red), and I (pink) filters. The I filter information is only taken from 2016, while the other filters are a combination of the data from 2014-2016. Stars V15, V16, and V20 only used data from 2016 for all filters. The best fit template from FITLC is overlaid

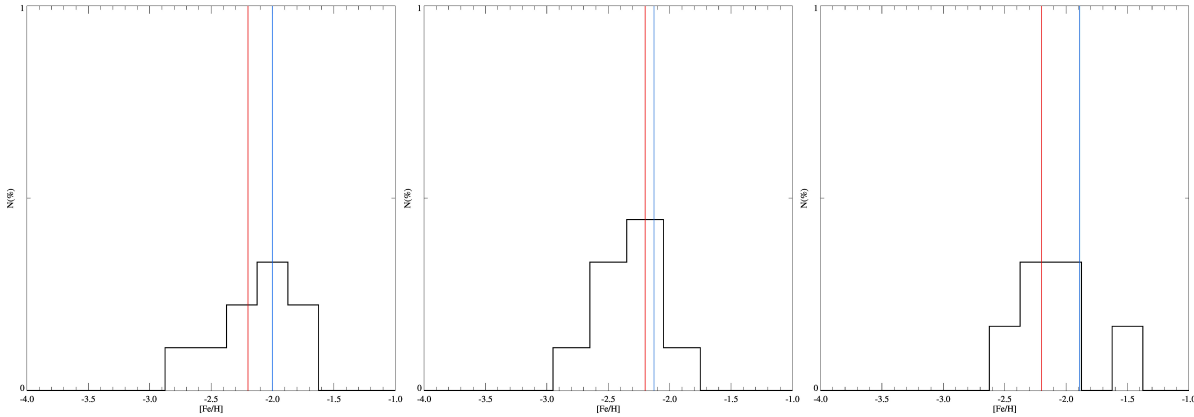


Figure 3.2 The metallicity results obtained using the Sarajendini method (left), Alcock method (middle), and Bono method (right) displayed in a histogram. The blue line is the mean metallicity for each method, and the red line is Ferro's metallicity. The standard deviation for my metallicity results are 0.097638, 0.062179, 0.084164, respectively.

each method which are displayed in Figure 3.2. The blue line is the mean value of the metallicity found by each method. Standard deviations for each method were found: the Alcock method is 0.062, the Bono method is 0.084, and the Sarajendini method is 0.097. The red line is the metallicity found by Ferro *et al.* (2008) in their work. The Bono method provided a mean result farthest from Ferro's mean, while the Sarajendini method had the largest standard deviation. The method that provided the closest metallicity value to Ferro *et al.* (2008) is the Alcock method.

while the blue line is the mean value of the metallicity found by each method. Standard deviations for each method were found: A00 is 0.062179, B07 is 0.084164, and S06 is 0.097638.

3.3 Period Comparison with Ferro *et al.* (2008)

Periods, like metallicity, also differ from the results in Ferro *et al.* (2008). Slight differences exist between the periods found with FITLC in this thesis for the RR Lyraes in NGC 5466. The periods found by FITLC and Ferro *et al.* are compared in Table 3.1. A few notable period differences can be seen in V15, V16, and V20. V20 has been known to exhibit strange pulsations, as mentioned by

Ferro *et al.* (2008). The changes in the periods for V15 and V16 can be attributed to the Blazhko effect. First noticed by Blazhko in 1907, this effect results in changes of the light curves of the RR Lyraes on a relatively short time scale, tens of days, producing a periodic modulation on the light curve. No explanation has been universally accepted for the Blazhko effect, but most theories stem from 2 possibilities: a consequence of some type of mixing of pulsation modes, or something related to magnetic cycles in the stars, perhaps coupled with rotation (Smith 1995).

Table 3.1 Period (in days) found by FITLC for each RR Lyrae compared to the periods found by Ferro *et al.* (2008). There different is noted.

Star	FITLC Period	Ferro Period	Difference
V2	0.588502	0.588502	0
V3	0.578065	0.578064	0.000001
V4	0.511307	0.511306	0.000001
V5	0.615224	0.615224	0
V6	0.620945	0.620951	0.000006
V7	0.703421	0.703420	0.000001
V8	0.629119	0.629118	0.000001
V9	0.685037	0.685036	0.000001
V10	0.709278	0.709278	0
V11	0.607705	0.607710	0.000005
V12	0.294239	0.294238	0.000001
V13	0.341557	0.341556	0.000001
V14	0.785856	0.785855	0.000001
V15	0.401845	0.398625	0.003220
V16	0.421832	0.419999	0.001833
V17	0.370106	0.370106	0
V18	0.374444	0.374443	0.000001
V20	0.190060	0.229496	0.039436
V21	0.791027	0.791027	0

3.4 Conclusion

Characteristics of globular clusters like NGC 5466 are studied for stellar evolution theories. Several attributes of NGC 5466 were determined using RR Lyrae light curves. Since light curves could change periodically because of the Blazhko effect, future work should be done to monitor the light curves. Data should also be gathered for V15, V16, and V20 to verify the periods I found with FITLC, since these three stars have the most noticeable differences in periods with Ferro *et al.* (2008), or perhaps determine if they are experiencing the Blazhko effect.

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Index

- Absolute brightness, 3
- Apparent brightness, 3
- Blazhko Effect, 16
- FITLC, 10
- Globular cluster, 1
- Hertzsprung-Russell Diagram, 3
- Light Curve, 13, 14
 - creating, 7
- Metallicity, 5, 11
- Photometry, 5, 7
- RR Lyrae, 3
 - RRab stars, 3, 11
 - RRc stars, 3
- Variable Stars, 3