DISTANCE ESTIMATION TO

RR LYRAE STAR BN VULPECULA

by

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DEPARTMENT APPROVAL

of a senior thesis submitted by

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This thesis has been reviewed by the research advisor, research coordinator, and department chair and has been found to be satisfactory.

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ABSTRACT

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RR Lyrae stars are variable stars with consistent pulsation periods. With these periods, we can estimate astronomical distances. The distance to RR Lyrae star BN Vulpecula was calculated using photometry methods and verified using the Gaia parallax method. This study verifies both of these methods for astronomical distance estimations.

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Chapter 1

Introduction

RR Lyrae stars provide important distance information in observational astronomy due to their well-defined pulsation properties and relatively uniform intrinsic luminosities. This makes them reliable standard candles for distance measurements. This chapter introduces the fundamental properties of RR Lyrae stars, explains the physics behind their pulsations, and outlines the objectives of this study, which focuses on determining the distance to the star BN Vulpecula using photometric methods and comparing the result to independent measurements.

1.1 RR Lyrae Stars

Variable stars are stars whose observed brightness, or luminosity, changes over time. These variations can arise from intrinsic processes within the star, such as pulsations, or from extrinsic causes, such as eclipses in binary systems.

RR Lyrae stars occupy a specific region of the Hertzsprung-Russell (HR) diagram known as the instability strip. These stars are low-mass, evolved stars that have left the main sequence and are currently in the phase where helium fusion occurs in

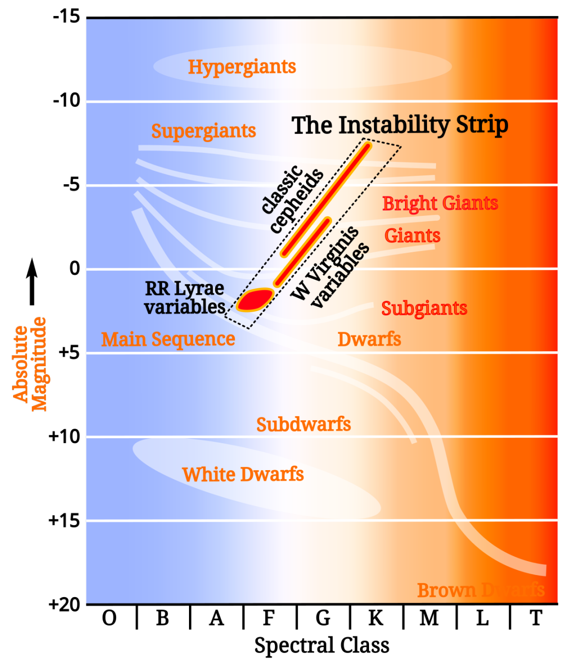

Figure 1.1 Hertzsprung-Russell Diagram [1]

the star's core while hydrogen burns in a surrounding shell. Partial ionization zones within these shells allow energy to be trapped and released. As a result, stars in this region of the HR diagram undergo regular pulsations that produce regular brightness variations.

RR Lyrae stars are pulsating variable stars whose brightness changes as their outer layers rhythmically expand and contract[2]. This behavior is driven by the κ-mechanism[3], which operates in a layer of partially ionized helium beneath the star's surface. In this region, helium does not remain in a single state. When the layer is relatively cool, much of the helium is only singly ionized and relatively transparent, allowing radiation from the star's interior to pass outward. However, as energy flows through the layer, it heats up, causing more helium atoms to lose an additional electron and become doubly ionized. In this state, the layer becomes significantly more opaque, trapping radiation beneath it. As energy builds up below this opaque layer, radiation pressure increases and pushes the outer layers of the star outward,

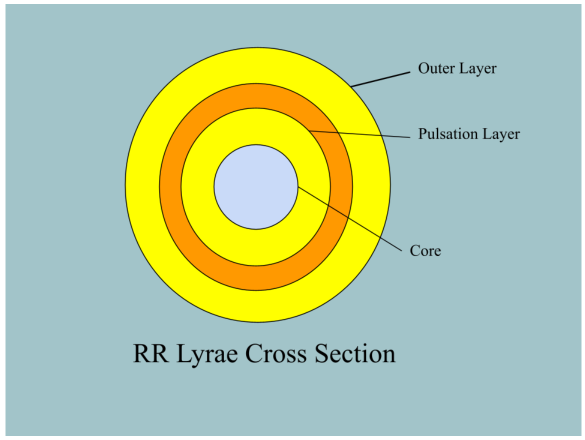

Figure 1.2 RR Lyrae Star Cross Section

causing the star to expand. During this expansion, the layer cools and its pressure drops, allowing the helium to recombine into a less ionized, more transparent state. The trapped energy is then released, escaping outward and reducing the internal pressure. Gravity then pulls the outer layers back inward, compressing and reheating the layer, and the cycle begins again. In this way, the ionization zone acts like a valve, regulating the flow of energy and driving the star's periodic pulsations.

RR Lyrae stars have pulsation periods of less than one day and relatively uniform absolute magnitudes, making them valuable standard candles for estimating astronomical distances. Their pulsation periods correlate with their luminosities, allowing distances to be estimated using period-luminosity–metallicity relations. One commonly used calibration is the Catelan relation:

$$M_\lambda = a + b \log P + c(\log Z)^2 \tag{1.1}$$

where M_λ is the absolute magnitude in photometric band λ, P is the period, Z is the heavy-element mass fraction (metallicity), and a, b, and c are coefficients that depend on wavelength[4]. Metallicity affects a star's opacity, with higher metallicity correlating to greater opacity and therefore cooler and slightly less luminous stars[5].

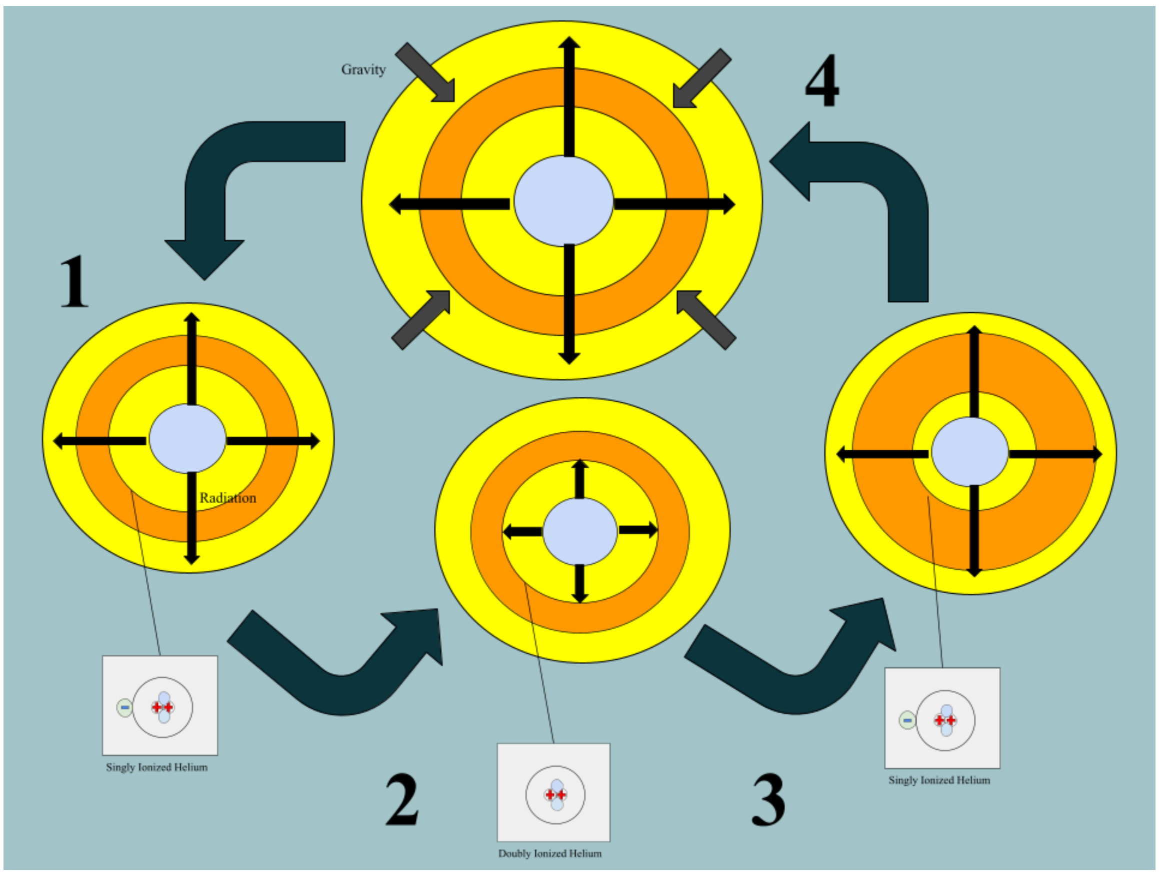

Figure 1.3 The κ-Mechanism

For our purposes, we used the Catelan equation for the V-band:

$$M_V = 2.288 + 0.882 \log Z + 0.108(\log Z)^2. \tag{1.2}$$

For the infrared filter, denoted as zs, we used:

$$M_{zs} = 0.839 - 2.195 \log P + 0.211 \log Z. \tag{1.3}$$

For the near-infrared filter, denoted as ip, we used:

$$M_{ip} = 0.908 - 1.035 \log P + 0.220 \log Z. \tag{1.4}$$

1.2 Project Background

Because RR Lyrae stars have relatively well determined absolute magnitudes, they are useful standard candle stars. A standard candle is an astronomical object with known luminosity and therefore a known absolute magnitude. Using these quantities, the distance can be calculated:

$$5 \cdot \log_{10} d = m - M + 5 - A \tag{1.5}$$

$$d = 10^{(m-M-A+5)/5} \tag{1.6}$$

where m is the apparent magnitude, M is the absolute magnitude, and d is the distance.

1.3 Goals

The goal of this project was to choose an RR Lyrae star with a previously undetermined distance. With the chosen star, the distance would then be calculated with Catelan's equations and AstroSource[6]. The distance would also be calculated using the Gaia parallax method[7] to check the accuracy of the Catelan distance.

Chapter 2

Methods

This chapter describes the methodology used in this study, including the selection of BN Vulpecula as the target star, the acquisition of photometric data through the Las Cumbres Observatory network, and the procedures used to process and analyze the data. The methods used to extract the pulsation period, measure apparent magnitudes, and apply period-luminosity-metallicity relations are also detailed, along with the approach used to compare the resulting distance with independent measurements from Gaia.

2.1 Target Selection

Candidate RR Lyrae stars were identified using the Variable Star Index available through the Journal of the American Association of Variable Star Observers (JAAVSO)[8]. In addition, the Our Solar Siblings (OSS) project[9] provided a spreadsheet catalog of RR Lyrae stars whose distances have either already been calculated or are currently under investigation[10]. Using these resources, several candidate stars were initially selected for further investigation.

Right Ascension (RA)	291.9835
Declination	24.3473

Table 2.1 BN Vul Coordinates

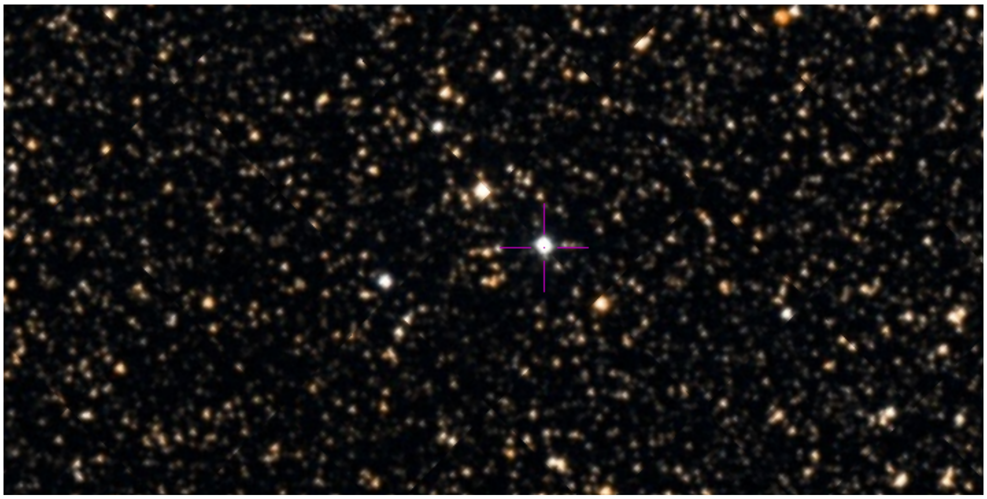

Figure 2.1 BN Vulpecula

Calibration observations of these candidate stars were requested through the Las Cumbres Observatory network (LCO). After these initial observations were completed and the resulting data were reviewed, the RR Lyrae star BN Vulpecula was selected as the target for this study. Its coordinates are given as

2.2 Observations

Follow-up observations of BN Vulpecula were obtained through the Las Cumbres Observatory[11] global telescope network. The star was monitored over a period of about two weeks. Observations were obtained using the SCICAM QHY600[12], a scientific CMOS camera equipped with a back-illuminated 61-megapixel Sony IMX455 sensor. The detector features 3.76 μm pixels, a full-frame format, and native 16-bit readout, providing high dynamic range and photometric precision . These observations were conducted using four photometric filters: Blue (B), Visual (V), infrared (ip), and near-infrared (zs). These observations produced a time series of images that allowed the brightness variations of the star to be measured over several pulsation cycles.

During the observation period, previously published literature on BN Vulpecula was also examined through the JAAVSO database in order to obtain physical parameters necessary for the analysis, particularly the star's metallicity.

2.3 Metallicity Conversion

The Catelan period–luminosity–metallicity relation requires the logarithm of the heavy element mass fraction, $\log Z$, rather than the reported iron abundance $[Fe/H]$. Thus, conversion between values is needed to accurately measure distance. The global metallicity $[M/H]$ accounts for the contribution of other elements, referred to as α-elements (Carbon, Oxygen, Neon, Magnesium, Silicon, Sulfur, Argon, Calcium, Titanium) are related to $[Fe/H]$ by

$$[M/H] = [Fe/H] + \log(0.638 f_\alpha + 0.362) \tag{2.1}$$

where $f_\alpha = 10^{0.3}$ is the α-element enhancement factor. For RR Lyrae stars, which are typically low in metal and high in α elements, this correction is important for accurately estimating the total metal content. The heavy element mass fraction Z is then found using:

$$Z = Z_{solar} \cdot 10^{[M/H]} \tag{2.2}$$

where Z_{solar} is the solar metallicity. Taking the logarithm gives:

$$\log Z = \log Z_{solar} + [M/H] \tag{2.3}$$

.

The metallicity values for BN Vulpecula were converted converted from $[Fe/H]$ to $\log Z$ and then used in the Catelan equations.

The resulting values are given below.

$[Fe/H]$	$[M/H]$	$\log Z$
-1.600	-1.386	-3.151

Table 2.2 Table of Metallicity Conversion

2.4 Data Reduction

After the observation period concluded, the LCO network compiled the imaging data and provided the observations in Flexible Image Transport System (FITS) format. FITS files contain the raw astronomical image data along with observational metadata.

These FITS files were imported into AstroImageJ, where aperture photometry was performed. For each image, an aperture radius was defined in order to measure the period of the target star while accounting for background light. The resulting photometric measurements were then exported as PSX files. This process was repeated for the data obtained in each of the four photometric filters.

2.5 Photometric Analysis

The PSX files were analyzed using AstroSource, a Python-based photometric analysis program developed by Michael Fitzgerald [6]. AstroSource processes time-series photometric data to determine the apparent magnitude of the star at each observation time and to estimate the pulsation period of the variable star.

Using these measurements, AstroSource produced light curves for BN Vulpecula in each photometric filter. These light curves show the periodic variation in brightness for BN Vulpecula. AstroSource operates with photometry (PSX) files and being given the coordinates of a certain star, it analyzes which stars have about the same magnitude. It then finds between 10 and 30 stars while the target star is flickering. It compares the target star's flickering to the magnitude of the comparison stars and then uses Fourier Analysis to create a lightcurve for the target star. It also determines the mid-value of apparent magnitude for the target star.

2.6 Distance Determination

To estimate the distance to BN Vulpecula, the apparent magnitudes and pulsation period obtained from AstroSource were used in combination with the Catelan period-luminosity-metallicity relation described in Section 2.1. The metallicity value used in this analysis was obtained from a study by Z. Kadla[**?**], which reported a metallicity of

$$[Fe/H] = -1.6. \tag{2.4}$$

The distance calculations were performed using the Catelan equations[10], and uncertainties in the measured quantities were propagated to estimate the associated errors in the final distance measurement.

Interstellar extinction was included in the distance determination through band-dependent extinction coefficients A_λ, which account for the dimming of apparent magnitude due to interstellar dust. The color excess for BN Vulpecula was obtained from the NASA/IPAC Infrared Science Archive (IRSA)[13] and was found to be $E(B-V) = 0.3355$.

Using standard extinction relations, wavelength-dependent extinction values were calculated for each photometric band. The resulting values are given in the following table.

Photometric Band	**Extinction A_λ (mag)**
V	1.04
ip	0.71
zs	0.51

Table 2.3 Band-dependent extinction values for BN Vulpecula

These extinction values were incorporated directly into the distance modulus calculation for each filter.

Because the extinction is significant, it plays an important role in accurately determining the distance, and uncertainty in these values contributes to the overall systematic uncertainty of the photometric distance estimate.

Distance estimates were calculated using the V, ip, and zs filters. The B filter was excluded from the final analysis because the results showed significant background radiation from nearby sources, which introduced additional noise into the photometric data. In addition to individual filter distance estimates, a combined distance was calculated by averaging the values obtained from the V, ip, and zs filters. This combined estimate is referred to as the Viz distance.

2.7 Comparison with Gaia Parallax

To assess the accuracy of the distance derived using the Catelan relation, an independent distance estimate was obtained using parallax measurements from the Gaia database[7]. The distance was calculated using the standard parallax–distance relation:

$$d = \frac{1}{p}, \tag{2.5}$$

where d is the distance in parsecs and p is the parallax in arcseconds. Since Gaia reports parallax in milliarcseconds (mas), this relation can be rewritten as

$$d = \frac{1000}{p}, \tag{2.6}$$

with p in milliarcseconds. The uncertainty is given by

$$\sigma_d = \frac{1000}{p^2}\sigma_p \tag{2.7}$$

where σ_p is observational uncertainty taken from Gaia data.

The parallax reported by Gaia is

$$p = 1.4481 \pm 0.0151 \text{ mas}. \tag{2.8}$$

It was compared with the value obtained from the photometric analysis. This comparison provided a consistency check on the distance determined from the RR Lyrae period–luminosity–metallicity relation.

Chapter 3

Results

The photometric analysis of BN Vulpecula yields quantitative measurements of its apparent magnitude, pulsation period, and resulting distance. This chapter presents the light curves obtained from observational data and the distance estimates calculated using the Catelan period-luminosity-metallicity relation. These results are then compared with an independent distance derived from Gaia parallax measurements to assess consistency and accuracy[7].

3.1 Photometric Measurements

The observational data obtained from the Las Cumbres Observatory network were analyzed using AstroSource[6]. Light curves were generated for the V, ip, and zs filters. The B filter was excluded from the final analysis due to significant contamination from background radiation and nearby sources.

From the AstroSource analysis, the average apparent magnitude of BN Vulpecula was determined to be

$$m = 10.75 \pm 0.01.$$

The pulsation period of the star was measured to be

$$P = 0.59 \pm 0.04 \text{ days}.$$

Light curves for the V, ip, and zs filters are shown in Figures 3.1, 3.2, 3.3, and 3.4.

Target Name	BN Vulpecula
Right Ascension (RA)	291.9836
Declination (Dec)	24.3474
Parallax	1.4481 mas
Metallicity	-1.6
Period	0.59

Table 3.1 Basic Properties of BN Vulpecula

3.2 Distance Estimates

Using the measured magnitude and the Catelan period–luminosity–metallicity relation described in Section 2, the photometric distance to BN Vulpecula was calculated. The resulting distance estimate was

$$d = 684 \pm 32 \text{ pc}.$$

An independent distance estimate was also obtained from parallax measurements in the Gaia archive[7]. The Gaia-derived distance was found to be

$$d = 690.6 \pm 8 \text{ pc.}$$

Distances were calculated independently for each filter and combined to produce a multi-band estimate (Viz), which provides a more robust distance measurement. The lightcurve plots in PSX are shown below for the V, zs, and ip -Band filters below.

	Distance	Error
Gaia	690.6	7
V	694	31
ip	690	47
zs	699	68
Viz	694	16

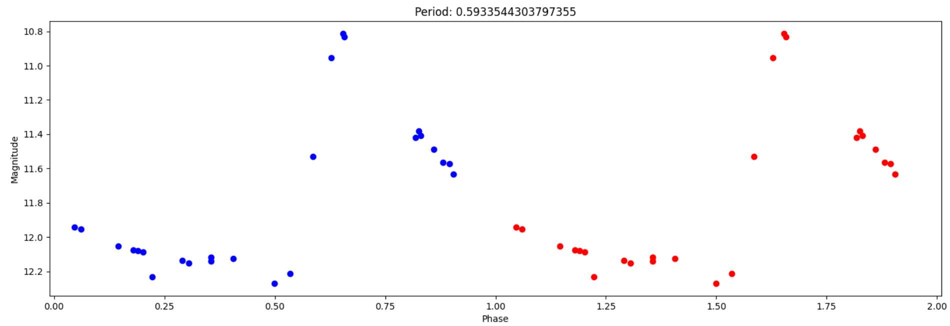

Figure 3.1 BN Vul B-Band Light-Curve

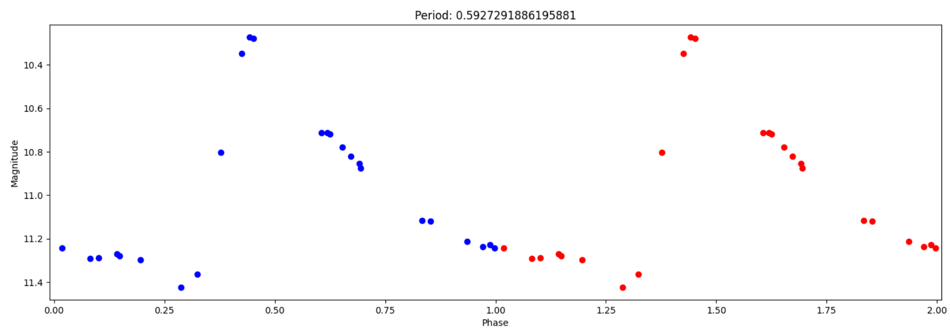

Figure 3.2 BN Vul V-Band Light-Curve

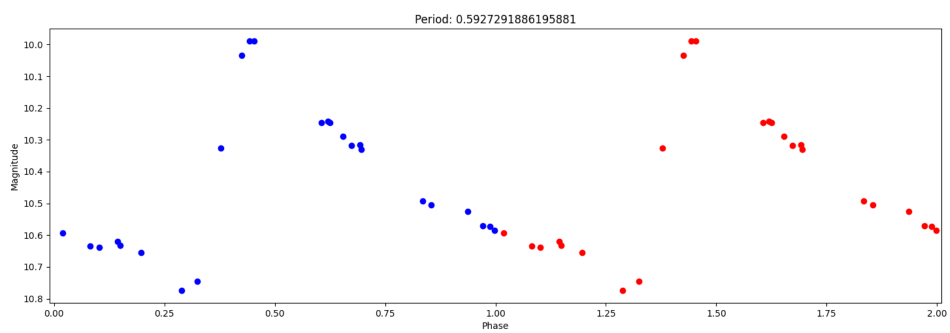

Figure 3.3 BN Vul ip-Band Light-Curve

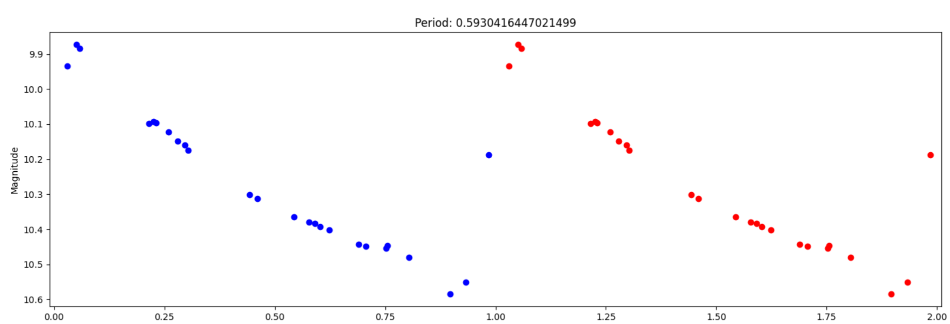

Figure 3.4 BN Vul zs-Band Light-Curve

Chapter 4

Discussion

Interpreting the results involves evaluating both the agreement between independent distance measurements and the uncertainties inherent in the analysis. This chapter examines the consistency between the photometric distance and the Gaia-derived distance, identifies key sources of uncertainty in the measurements, and considers the implications of these findings for the use of RR Lyrae stars as standard candles. The reliability of the methods used in this study is assessed, and potential improvements for future analyses are discussed.

4.1 Comparison with Gaia Distance

The photometric distance obtained using the Catelan period–luminosity–metallicity relation was found to be 684 ± 32 pc. This is in strong agreement with the distance derived from Gaia parallax measurements, which was calculated to be 690.6 ± 8 pc. The difference between these two values is only 6 pc, which lies well within the uncertainty of the photometric estimate.

This agreement suggests that the Catelan relation provides a reliable method for estimating distances to RR Lyrae stars when accurate measurements of magnitude, period, and metallicity are available. The Gaia distance uses more precise measurements, while the photometric method uses calibrated relationships between the pulsation properties of stars and intrinsic luminosity. The consistency between these two independent methods supports the validity of the photometric analysis performed in this study.

4.2 Sources of Uncertainty

Although the photometric distance estimate agrees well with the Gaia result, several sources of uncertainty affect the measurement. One source of uncertainty arises from the measurement of the apparent magnitude and pulsation period derived from the AstroSource analysis. Small uncertainties in these quantities propagate through the Catelan relation and contribute to the final uncertainty in the calculated distance. Another important source of uncertainty is the metallicity value used in the calculation. The metallicity of BN Vulpecula was obtained from previously published literature, and any uncertainty in this value depends on metallicity. Variations in $[Fe/H]$ can lead to corresponding variations in the estimated distance. Observational limits also introduce noise into photometric data. For example, the B filter observations were not included in the final analysis due to the contamination from background radiation. This contamination increased the uncertainty in the measured brightness of the target star in that filter, making it unsuitable for reliable distance estimation. In addition to these sources of uncertainty, extinction-corrected magnitudes were calculated as part of the analysis. These corrections are intended to account for the effects of interstellar dust, which can absorb and scatter light, causing stars to appear dimmer than their absolute magnitude would suggest.

	Distance	Error
Gaia	690.6	7
V	694	31
ip	690	47
zs	699	68
Viz	694	16

4.3 Implications for RR Lyrae Distance Measurements

RR Lyrae stars are widely used as standard candles for measuring distances within the Milky Way and nearby galaxies. Their relatively uniform luminosities and pulsation properties allow estimations of distances.

The results of this study demonstrate that photometric methods based on the Catelan relation can produce distance estimates that are consistent with measurements from Gaia. This agreement highlights the usefulness of RR Lyrae stars as standard candles.

Future observations with improved photometric precision and longer time coverage could further refine the distance estimate for BN Vulpecula. Additional measurements in infrared bands, where RR Lyrae period–luminosity relations are often tighter, may also reduce uncertainties in photometric distance determinations.

Chapter 5

Conclusion

This study demonstrates the effectiveness of RR Lyrae stars as distance indicators through the analysis of BN Vulpecula. By combining photometric observations with established period-luminosity-metallicity relations, a distance estimate was obtained that is consistent with independent measurements from Gaia. These results reinforce the reliability of RR Lyrae stars as standard candles and highlight the value of combining observational data with theoretical models. Future work may further refine these measurements through improved photometric precision and expanded observational coverage.

5.1 Conclusion

In this study, the RR Lyrae star BN Vulpecula was observed using the Las Cumbres Observatory network and analyzed with AstroSource. Photometric measurements of its apparent magnitude and pulsation period were used in combination with the Catelan period–luminosity–metallicity relation to estimate its distance.

The photometric distance was found to be 684 ± 32 parsecs, in strong agreement with the Gaia-derived distance of 690.6 ± 8 parsecs. This agreement shows that photometric methods and Gaia may be used to verify one another.

These results show that RR Lyrae stars may be used as standard candles for mapping astronomical distances, particularly at ranges that are beyond the scope of parallax methods. Future studies with higher-precision photometry, longer observation campaigns, and measurements in additional photometric bands could further refine distance determinations for BN Vulpecula and other RR Lyrae stars.

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