A NEW PHOTOMETRIC DETERMINATION OF THE DISTANCE TO THE RR LYRAE STAR RS BOÖTES

by

Isaac Hjelm

A senior thesis submitted to the faculty of

Brigham Young University - Idaho

in partial fulfillment of the requirements for the degree of

Bachelor of Science

Department of Physics

Brigham Young University - Idaho

April 2026

Copyright © 2026 Isaac Hjelm

All Rights Reserved

BRIGHAM YOUNG UNIVERSITY - IDAHO

DEPARTMENT APPROVAL

of a senior thesis submitted by

Isaac Hjelm

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

Date	Richard Datwyler, Advisor
Date	Stephen McNeil, Committee Member
Date	Kevin Kelley, Committee Member
Date	Todd Lines, Thesis Coordinator
Date	Evan Hansen, Department Chair

ABSTRACT

A NEW PHOTOMETRIC DETERMINATION OF THE DISTANCE

TO THE RR LYRAE STAR RS BOÖTES

Isaac Hjelm

Department of Physics

Bachelor of Science

This study measured the apparent magnitudes of the RR Lyrae star RS Boötes over an approximately two week period using telescopes from the Las Cumbres Observatory (LCO), and used equations from the Catelan 2004 and Catelan 2008 studies to find the absolute magnitudes. Using the period-luminosity-metallicity relations and LCO observations, the distance based on averaged results from the visual, near-infrared, and far-red filters of RS Bootes is estimated to be 733 ± 45 parsecs. This is comparable to GAIA's parralax distance measurements of 745 ± 9.5 parsecs.

ACKNOWLEDGMENTS

I would like to thank Michael Fitzgerald and Our Solar Siblings, whose resources and guidance provided the means to conduct this study. I'd also like to acknowledge the astronomical databases and resources we utilized in this research including: Aladin, SIMBAD, Peranso, the Las Cumbres Observatory, the AAVSO's Variable Star Index, and the ESA's GAIA data releases.

I would also like to thank my advisor Richard Datwyler for being my mentor in this study, as well as for starting me on my physics journey.

A very genuine thank you to my parents and siblings for the support they have given me over my time as a physicist, and in all the time before. My gratitude both to and for them can never be fully expressed.

Contents

Table of Contents vii

List of Figures viii

1 Introduction 1
1.1 Background Theory and Principles 2

2 Observations and Methods 4
2.1 Observations 4
2.2 Methods 6

3 Results and Discussions 9
3.1 Error Analysis 9

4 Conclusion 13

Bibliography 14

A B Filter Calibration Star Table and Associated Map 17

B V Filter Calibration Star Table and Associated Map 20

C ip Filter Calibration Star Table and Associated Map 23

D zs Filter Calibration Star Table and Associated Map 25

List of Figures

3.1 B-band light curve 10
3.2 V-band light curve 10
3.3 ip-band light curve 11
3.4 zs-band light curve 11
3.5 Calculated Distances with Error compared to GAIA 12

A.1 B Filter Calibration star map of RS Boo created using Aladin 18

B.1 V FilterCalibration star map of RS Boo created using Aladin 21

C.1 ip FilterCalibration star map of RS Boo created using Aladin 24

D.1 zs FilterCalibration star map of RS Boo created using Aladin 26

Chapter 1

Introduction

RR Lyrae stars are a type of helium fusing star that pulsate with a predictable brightness. These stars are used by astronomers as a tool called standard candles, which are used to determine distances between astronomical objects. The time it takes them to pulsate lasts anywhere between 5 to 24 hours, and they have a mass between 60 and 80 percent of our Sun. The pulsation and clustering of these RR Lyrae stars allow astronomers to determine distances to objects in our galaxy. The fact that they pulsate with predictable times and brightnesses allows us to use mathematical relations to determine both their distance, and their magnitude from Earth. This paper presents the results of a study of the RR Lyrae star RS Boötes (hereafter referred to as RS Boo) using an analysis of its pulsation period and resulting light curves.

RS Boo is a RR Lyrae star located in the Boötes constellation. RS Boo was chosen for its magnitude and favorable visibility from the telescopes used in this study. Our study collected data from the Las Cumbres Observatory (LCO) Observation Portal[1]. The LCO telescopes collected data in four different image filter types: blue (B), visual (V), near-infrared (ip), and far-red (zs). The returned images were processed through a python package called *Astrosource*[2]. The *Astrosource* code was used to process the images and estimate the apparent magnitude and period in each filter. Presented alongside the estimations were the light curves of the star over time, from which we found the amplitude.

Once the distance to RS Boo was determined from our collected data, we compared it to other studies which calculated the distance. Studies like this are important because they allow for the verification of distance calculations and the methods used for them.

1.1 Background Theory and Principles

RR Lyrae stars pulsate, meaning that their magnitude from Earth oscillates over time. This is understood to be primarily caused by what is called the κ mechanism. In the second helium ionization zone, the partially ionized helium within the stellar envelope changes opacity depending on how compressed the gas becomes. As the ionized helium becomes more compressed its opacity increases, and it traps in radiation and energy causing a rise in temperature and pressure. While the opacity is increased it causes a temporary block of the radiative flux of the star. The increased temperature and pressure causes the gas to expand and decrease its opacity. This allows the energy to be released, and the temperature drops. The gas compresses in the cooler temperature, and the whole cycle repeats itself. This is referred to as an Eddington valve, and is the primary cause behind the pulsation of pulsating variable stars.

Metallicity is used to describe the abundance of elements heavier than helium within a star. The metallicity effects the opacity of the stellar envelope, and thus the absolute magnitude of the star is dependent on its metallicity. In this study specifically the proportion of iron to hydrogen (Fe/H) contained in RS Boo was used.

The Interstellar Extinction Value (A) acts as a way to account for interstellar dust between the star and the observer. The values for A in each filter were found based off of an interstellar reddening value $E(B-V)$ given in the NASA/IPAC Infrared Science Archive[3].

The photometry used in this study is known as Source Extractor Kron (SEK) photometry[4]. This type of photometry is a modified version of Source Extractor photometry that utilizes Kron apertures[5]. The photometry system identifies the source of light, algorithmically defines and subtracts the background light, then defines an aperture based off the brightness distribution. The system then calculates the brightness from that source within the defined aperture.

GAIA is the Global Astrometric Interferometer for Astrophysics (GAIA) satellite[6]. In the late 2010s, GAIA used a method known as parallax to determine the most accurate distances to stars to date. Due to its accuracy GAIA's calculations were used as a baseline comparison to check the accuracy of our own calculated distance. It is important to note that unlike photometry, parallax uses geometry to calculate distances to astronomical objects. Comparing results from multiple methods of analysis helps verify the accuracy of the calculations. This study acts as a determination of the distance to RS Boo, as well as a verification of using photometry to determine distance.

Chapter 2

Observations and Methods

In order to determine the distance to RS Boo some crucial data had to be collected. Using telescopes we were able to observe the star over a period of roughly 2.5 weeks. This allowed us to collect data on the period and magnitude of RS Boo.

2.1 Observations

The telescope data used for this study was obtained through the Las Cumbres Observatory (LCO). Their 0.4 meter telescopes equipped with QHY 600 CMOS cameras[7] were used to collect our data. Initially a request for just one image in each filter for an allotted amount of exposure time was submitted. Each filter requires different amounts of time to get images with good enough definition and quality to use to obtain data from which to base our estimates. This initial request was used as a test to finalize the exposure times and the number of images that we needed to submit to LCO to get the proper quantities of data. For the cadence test we requested 79 image requests on each of the four filters, with each filter having a set exposure time shown in table 2.1.

Table 2.1 Calibrated times requested of each filter

Filter Type	Calibrated Exposure Times (s)
B	23
V	15
ip	35
zs	177

Once our images were returned they were processed through the python package *Astrosource*. The *Astrosource* package applied an analysis method called differential SEK photometry to the images and returned estimations of RS Boo's magnitude, pulsation period, and light curves. Differential photometry compares the magnitude of the target star to the magnitude of surrounding stars to derive a more accurate calibrated magnitude. SEK photometry allows for more precise analysis as explained in section 1.1. In the analysis, magnitudes from the PanSTARRS[8] and APASS[9] catalogs were used to calibrate the measured photometry using nearby catalog stars. From these estimations and mathematical relations, the distance to RS Boo was calculated. These light curves can be seen in figs. 3.1 to 3.4.

The absolute magnitude of RS Boo was calculated using the metallicity of the star and equations from the Catelan studies in 2004[10] and 2008[11]. Other studies have already been done to find the metallicity of RS Boo, and reported it to be Fe/H = -0.36 [12]. The Our Solar Siblings course[13] by Michael Fitzgerald gave us an Excel sheet of calculations[14] to plug our data into. The sheet applied our data to the equations from the Catelan studies, and returned estimates of distance, the error in the distance calculations, and the interstellar extinction value. These equations and their results are explained in the following section. Between all four color filters we got an apparent magnitude between 10.3 and 10.6, and a period of 0.378 ± 0.010 days.

2.2 Methods

To determine the distance to RS Boo from its magnitude, the distance modulus:

$$m - M = 5\log(d) - 5 \; + A$$

is used. This formula uses the absolute magnitude M, apparent magnitude m, and the interstellar extinction value A to determine the distance to the star in parsecs d. The apparent magnitude is the middle magnitude from the light curves returned by the Astrosource code. The light curves resulting from our data for each filter can be seen in figs. 3.1 to 3.4.

The Catelan 2004 study showed that the absolute magnitude in the V filter (M_V) is given by:

$$M_V = 2.288 + 0.882\log(Z) + 0.108\log(Z)^2,$$

where Z is the metallicity, and $\log(Z)$ is found from the equation:

$$\log(Z) = [\mathrm{Fe/H}] + \log(0.638 \times 10^{0.3} + 0.632) - 1.765.$$

The absolute magnitude for the ip and zs filters can be found from the following equations from the Catelan 2008 study. P is defined to be the period of the star in these equations:

$$M_i = 0.908 - 1.035\log(P) + 0.220\log(Z),$$

$$M_z = 0.839 - 1.295 \log(P) + 0.211 \log(Z).$$

The equations do not use the B filter in determining distance, but it was used to ensure accuracy in our measurements by comparing the estimated middle magnitudes.

With all these values the distance modulus can be rearranged to compute the distance through:

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

After deriving the distances in each filter, the results were compared to previously conducted studies. This was done by comparing an average of the three distances computed from our data to the distances computed by GAIA.

To ensure the best quality of data we calibrated our exposure times for an optimal brightness range in each image. The goal was to obtain between 100,000 and 300,000 counts in each image. This returns good quality data in each image, but avoids saturating the images which would deteriorate the data quality. Using AstroImageJ[15] we measured the total number of counts for a given exposure time, calculated the counts per second, and adjusted the exposure times to fit this range. This also allowed the submission of a single optimized image request to LCO, improving both quality and efficiency.

The *Astrosource* code calibrated the magnitude measurements by comparing RS Boo to nearby non-variable stars. A map of the calibration stars used in our study obtained from Aladin[16] alongside their associated magnitudes can be found in Appendix A for each filter. Since these comparison stars have constant magnitudes, their known values can be used to convert the measured counts into calibrated magnitudes. This allowed us to accurately track how RS Boo's brightness changed over time.

The middle magnitude helps us to understand and calculate the distance using the distance modulus equation explained earlier. The middle magnitude describes the average/apparent magnitude of our star compared to other surrounding stars that may differ in magnitude. Through this selected magnitude our star can be isolated and assumptions on its distance can be made. The calculated middle magnitudes and distances from our data can be seen in tables 3.1 and 3.2 respectively.

Taking the data gathered, along with the data given by GAIA, we can conclude that our apparent estimations of RS Boo's distance is within a reasonable range of error, meaning our numbers and calculations are close to GAIA's. The results from our data and calculations will be given in the following section.

Chapter 3

Results and Discussions

The data from our study computed a distance of 733 $\pm$ 45 parsecs. This compares to GAIAs computed parallax distance of 745.108 $\pm$ 9.5 parsecs. The distances in each filter and how they compare to GAIA data can be seen in figure 3.5

3.1 Error Analysis

The differences between our calculation and previously published values, as well as the larger uncertainties can be partially attributed to the image quality. In some cases the images experienced interference during the exposure time by atmospheric or transient obstructions such as clouds or passing satellites. In other cases the light curves are scattered by additional brightness generating additional counts of data. This is visible in the light curve of the V filter(figure 3.2). The light curve from our data is more scattered due to the interference during the exposure time of our images. This generates increased uncertainty in the apparent magnitude and computed distance.

Another source of error is the limiting of our sample size. Our image request to

LCO consisted of 79 images per filter, but only 70 were successfully captured—the remaining 9 could not be completed due to the telescope's inability to observe the target in time. Of the 70 images taken, only 27 were processed and returned to us. With fewer data points, variability and measurement noise have a greater impact on the derived light curves, magnitudes, and distance estimates.

If we were to redo this study, we would better account for this with stricter image filtering and obtaining more images so that we have a larger and more precise data sample. This would allow for better and tighter light curves, with a more accurately computed magnitude and distance. Despite these limitations, our derived values remain consistent with independent measurements from Gaia within the reported uncertainties.

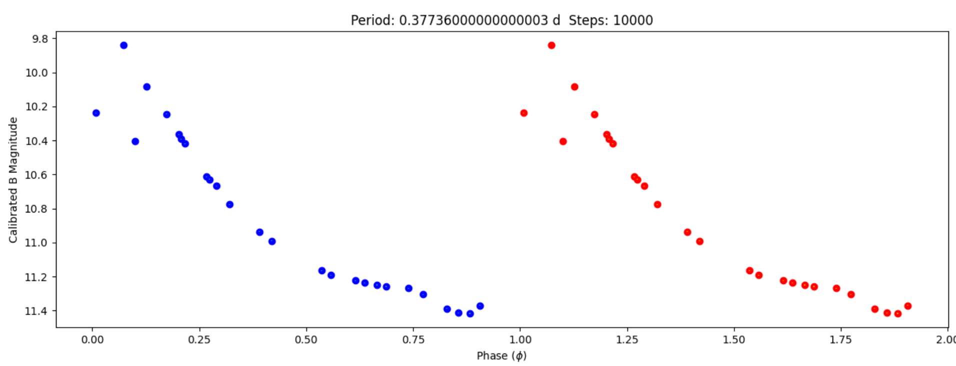

Figure 3.1 B-band light curve

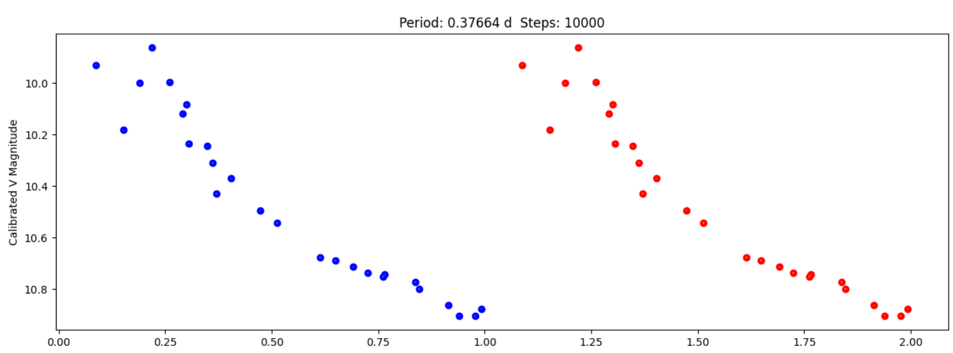

Figure 3.2 V-band light curve

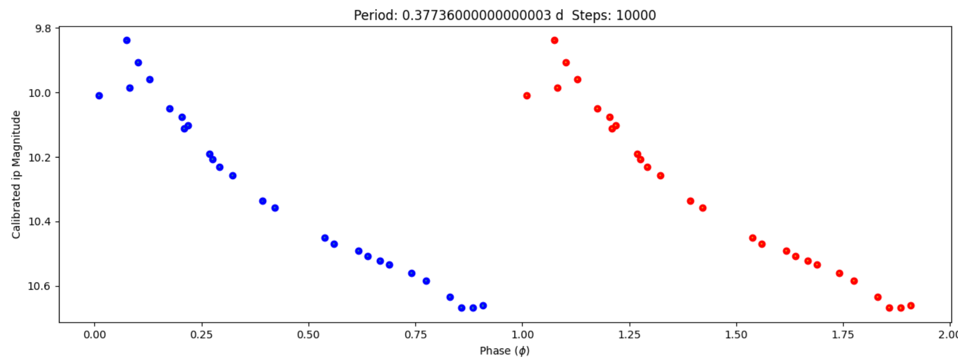

Figure 3.3 ip-band light curve

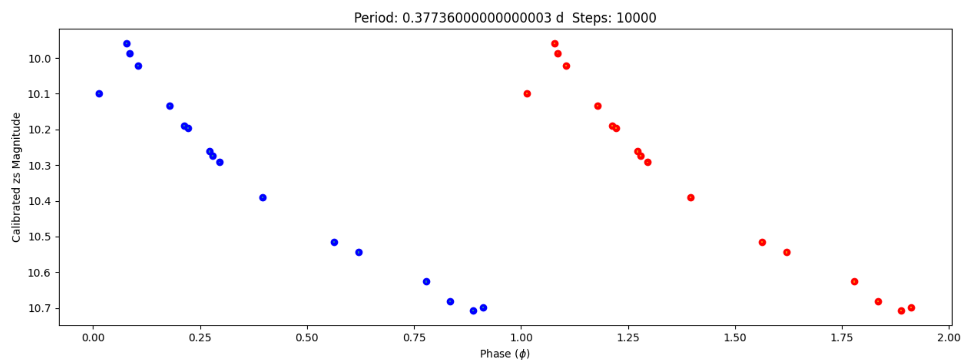

Figure 3.4 zs-band light curve

Table 3.1 Middle Magnitude of Each Filter Type

Filter Type	Middle Magnitude	Error
B	10.627	±0.19
V	10.382	±0.18
i_p	10.253	±0.10
z_s	10.332	±0.18

Table 3.2 Calculated Distance of Each Filter Type

Filter Type	Distance (pc)	Error (pc)
GAIA	745	±9.5
V	740	±101
i_p	725	±53
z_s	735	±79
Viz	733	±45

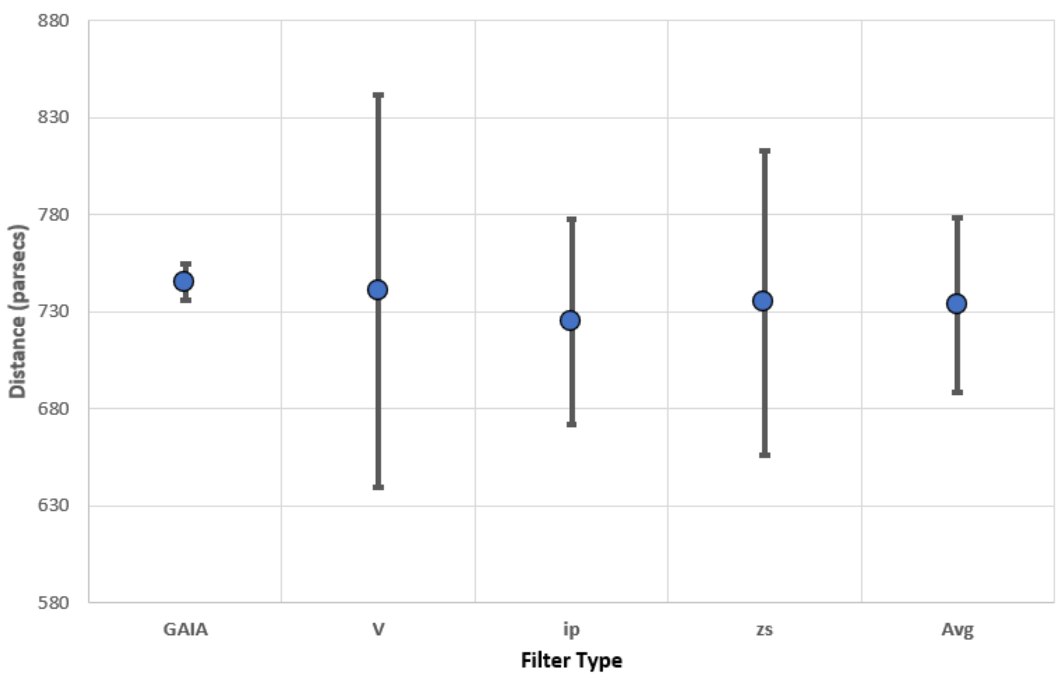

Figure 3.5 Calculated Distances with Error compared to GAIA

Chapter 4

Conclusion

The goal of this study was to use SEK photometry and telescope data to estimate the distance to the RR Lyrae star RS Boötes and compare the result to established measurements. Our analysis produced an estimated distance of 733 ± 45 parsecs. This value is consistent with GAIA's parallax-based measurement of 745.1 ± 9.5 parsecs, since the value falls within the combined uncertainties of our data.

Our photometric estimate being consistent alongside that of GAIA indicates that our methods produce accurate and reliable estimations of distance. This study and its agreement with other measurements, supports the effectiveness of SEK photometry in predicting distances to RR Lyrae stars. With more observations and lessened interference, future studies could find distances to RR Lyrae stars with greater precision and confidence.

Bibliography

[1] T. M. Brown *et al.*, "Las Cumbres Observatory global telescope network," Publications of the Astronomical Society of the Pacific **125,** 1031–1055 (2013).

[2] M. Fitzgerald, E. Gomez, S. Salimpour, J. Singleton, and R. Wibowo, "Astrosource: Automating optical astronomy measurement, calibration and analysis for variable stellar sources from provided photometry," Journal of Open Source Software **6,** 2641 (2021).

[3] D. J. Schlegel, D. P. Finkbeiner, and M. Davis, "Maps of Dust Infrared Emission for Use in Estimation of Reddening and Cosmic Microwave Background Radiation Foregrounds," **500,** 525–553 (1998).

[4] E. Bertin and S. Arnouts, "Sextractor: Software for source extraction," Astronomy and Astrophysics Supplement Series **117,** 393–404 (1996).

[5] "All-Sky Data Release Explanatory Supplement: Data Processing,".

[6] A. Vallenari *et al.*, "Gaia Data Release 3: Summary of the content and survey properties," Astronomy amp; Astrophysics **674,** A1 (2023).

[7] Webadmin, "QHY600PH series (IMX455) astronomy cooling camera: QHYCCD,", 2025.

[8] H. A. Flewelling *et al.*, "The Pan-STARRS1 Database and Data Products," The Astrophysical Journal Supplement Series **251,** 7 (2020).

[9] A. A. Henden, M. Templeton, D. Terrell, T. C. Smith, S. Levine, and D. . Welch, "VizieR Online Data Catalog: AAVSO Photometric All Sky Survey (APASS) DR9 (Henden+, 2016)," AAVSO **II,** 336 (2016).

[10] M. Catelan, B. J. Pritzl, and H. A. Smith, "The RR Lyrae Period–Luminosity Relation. I. Theoretical Calibration," The Astrophysical Journal Supplement Series **154,** 633–649 (2004).

[11] C. Cáceres and M. Catelan, "The Period–Luminosity Relation of RR Lyrae Stars in the SDSS Photometric System," The Astrophysical Journal Supplement Series **179,** 242–248 (2008).

[12] G. Bras *et al.*, "The Baade-Wesselink projection factor of RR Lyrae stars—Calibration from OHP/SOPHIE spectroscopy and Gaia DR3 parallaxes," Astronomy & Astrophysics **684,** A126 (2024).

[13] M. Fitzgerald, "The Our Solar Siblings Pipeline," Robotic Telescopes, Student Research and Education Proceedings 1 (2018).

[14] M. Fitzgerald, "Our Solar Siblings Photometry Calculation Spreadsheet,", 2025, instructional spreadsheet provided in the Our Solar Siblings course.

[15] K. A. Collins, J. F. Kielkopf, K. G. Stassun, and F. V. Hessman, "Astroimagej: Image processing and photometric extraction for ultra-precise astronomical light curves," The Astronomical Journal **153,** 77 (2017).

[16] F. Bonnarel, P. Fernique, O. Bienaymé, D. Egret, F. Genova, M. Louys, F. Ochsenbein, M. Wenger, and J. G. Bartlett, "The Aladin interactive sky at-

las. A reference tool for identification of astronomical sources," Astronomy and Astrophysics Supplement Series **143,** 33–40 (2000).

Appendix A

B Filter Calibration Star Table and Associated Map

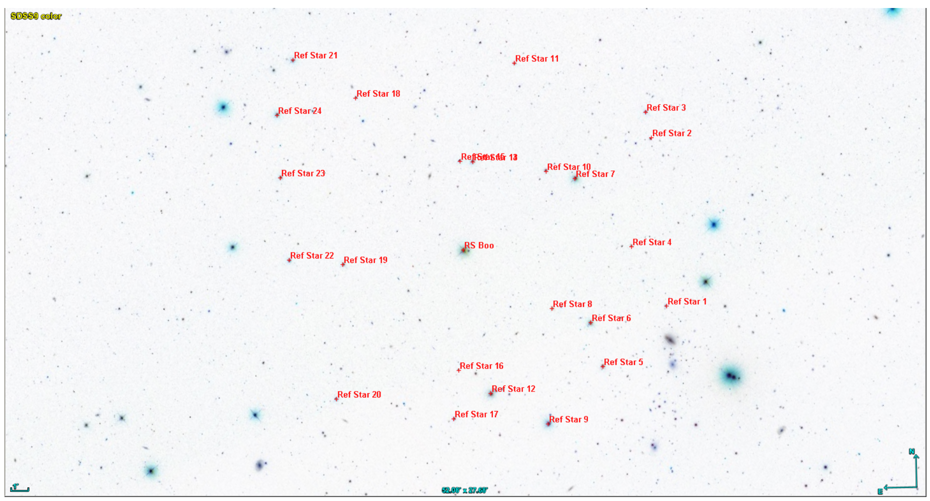

Figure A.1 B Filter Calibration star map of RS Boo created using Aladin

Table A.1 B Filter Calibration Stars and Their Properties From Astrosource

Calibration Star	RA	Dec	Magnitude	MagDiff
1	218.1644	+31.7019	15.334	0.0285
2	218.1816	+31.8593	15.266	0.0282
3	218.1870	+31.8852	14.459	0.0157
4	218.2028	+31.7584	15.378	0.0260
5	218.2345	+31.6451	13.568	0.0122
6	218.2482	+31.6866	13.048	0.0061
7	218.2652	+31.8226	12.307	0.0060
8	218.2912	+31.6998	14.555	0.0152
9	218.2951	+31.5914	12.665	0.0092
10	218.2973	+31.8295	14.178	0.0091
11	218.3323	+31.9312	14.848	0.0190
12	218.3584	+31.6201	12.378	0.0056
13	218.3752	+31.6389	15.197	0.0206
14	218.3785	+31.8384	13.725	0.0107
15	218.3926	+31.8390	14.446	0.0121
16	218.3941	+31.6421	15.336	0.0255
17	218.3995	+31.5962	14.958	0.0192
18	218.5083	+31.8982	15.203	0.0194
19	218.5225	+31.7414	14.402	0.0156
20	218.5296	+31.6146	14.948	0.0235
21	218.5782	+31.9340	14.138	0.0125
22	218.5819	+31.7456	14.526	0.0200
23	218.5921	+31.8232	14.264	0.0113
24	218.5956	+31.8821	13.755	0.0120

Appendix B

V Filter Calibration Star Table and Associated Map

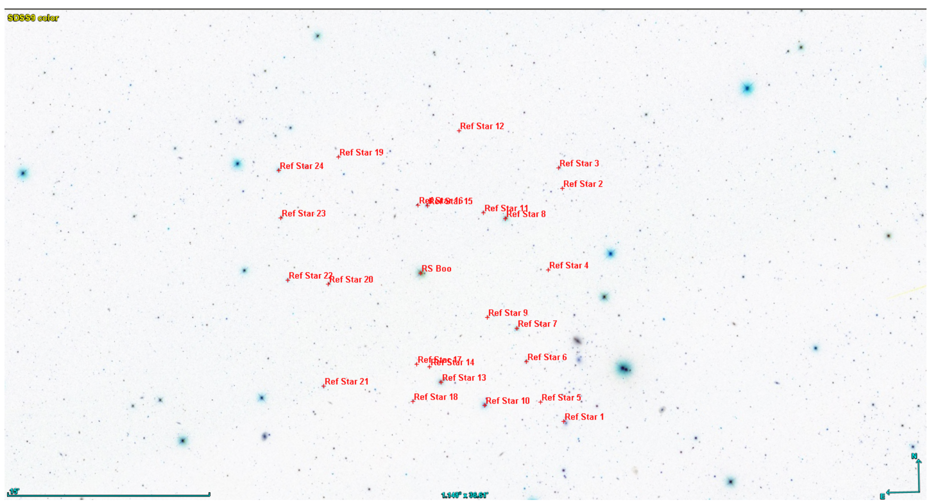

Figure B.1 V FilterCalibration star map of RS Boo created using Aladin

Table B.1 V Filter Calibration Stars and Their Properties From Astrosource

Calibration Star	RA	Dec	Magnitude	MagDiff
1	218.1801	+31.5711	14.066	0.0144
2	218.1816	+31.8593	14.554	0.0179
3	218.1870	+31.8852	13.562	0.0116
4	218.2028	+31.7584	14.570	0.0190
5	218.2140	+31.5947	14.809	0.0220
6	218.2344	+31.6451	12.927	0.0088
7	218.2482	+31.6866	12.255	0.0070
8	218.2652	+31.8225	11.708	0.0052
9	218.2911	+31.6998	13.941	0.0177
10	218.2951	+31.5915	11.673	0.0051
11	218.2973	+31.8294	13.587	0.0113
12	218.3323	+31.9311	14.301	0.0113
13	218.3584	+31.6201	11.805	0.0057
14	218.3752	+31.6389	14.508	0.0164
15	218.3785	+31.8383	12.973	0.0082
16	218.3926	+31.8390	13.707	0.0118
17	218.3941	+31.6421	14.745	0.0219
18	218.3995	+31.5962	14.076	0.0176
19	218.5083	+31.8981	14.381	0.0189
20	218.5225	+31.7413	13.526	0.0097
21	218.5296	+31.6146	13.895	0.0141
22	218.5819	+31.7455	13.493	0.0099
23	218.5921	+31.8231	13.509	0.0141
24	218.5956	+31.8819	12.857	0.0085

Appendix C

ip Filter Calibration Star Table and Associated Map

Table C.1 ip Filter Calibration Stars and Their Properties From Astrosource

Calibration Star	RA	Dec	Magnitude	MagDiff
1	218.1720	+31.6073	14.567	0.0285
2	218.1802	+31.5711	15.729	0.0135
3	218.1817	+31.8593	14.245	0.0183
4	218.2029	+31.7585	14.179	0.0180
5	218.3323	+31.9312	13.940	0.0173
6	218.3752	+31.6390	14.101	0.0192
7	218.3941	+31.6421	14.406	0.0244
8	218.4501	+31.7169	14.368	0.0315
9	218.5083	+31.8982	13.835	0.0168
10	218.5445	+31.5823	14.514	0.0270

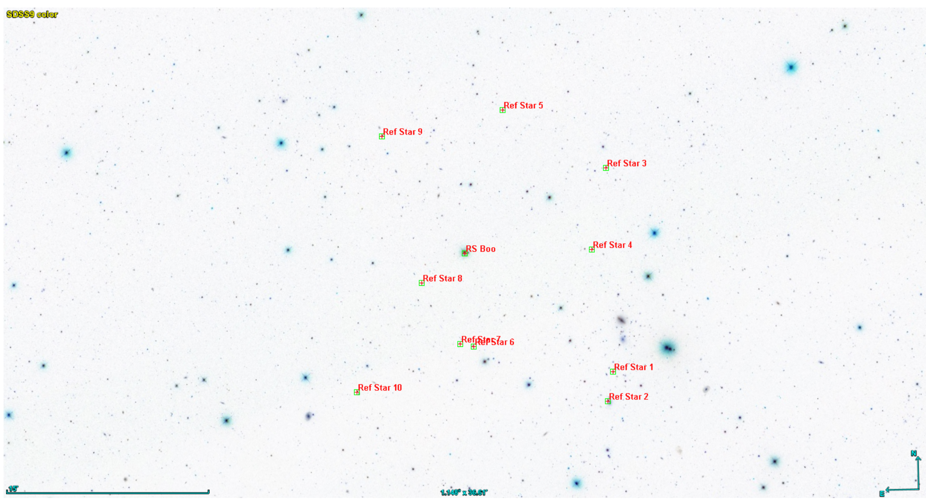

Figure C.1 ip FilterCalibration star map of RS Boo created using Aladin

Appendix D

zs Filter Calibration Star Table and Associated Map

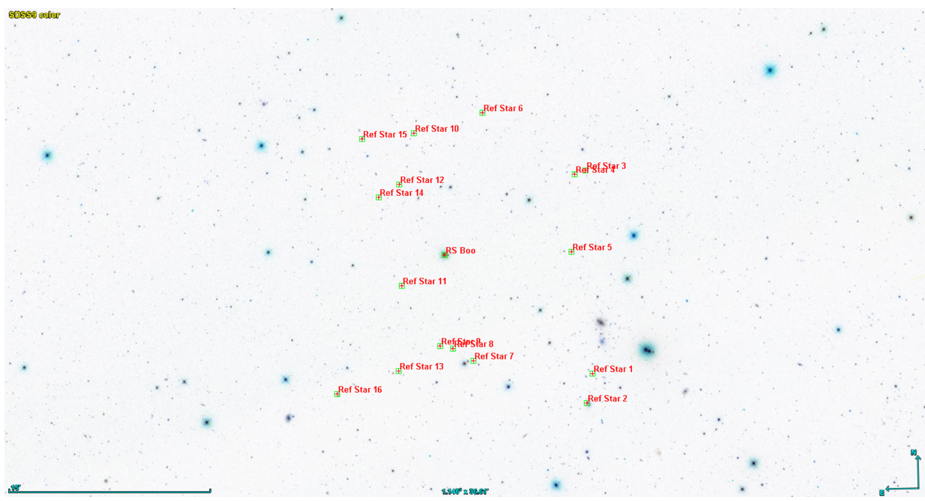

Figure D.1 zs FilterCalibration star map of RS Boo created using Aladin

Table D.1 zs Filter Calibration Stars and Their Properties From Astrosource

Calibration Star	RA	Dec	Magnitude	MagDiff
1	218.1720	+31.6073	14.513	0.0369
2	218.1802	+31.5710	13.536	0.0230
3	218.1817	+31.8593	14.242	0.0287
4	218.1977	+31.8550	14.704	0.0335
5	218.2029	+31.7585	14.137	0.0212
6	218.3324	+31.9313	13.935	0.0186
7	218.3458	+31.6235	14.318	0.0314
8	218.3752	+31.6389	14.056	0.0307
9	218.3941	+31.6421	14.376	0.0339
10	218.4330	+31.9054	14.077	0.0248
11	218.4501	+31.7169	14.323	0.0166
12	218.4543	+31.8422	14.547	0.0289
13	218.4548	+31.6106	14.217	0.0270
14	218.4842	+31.8264	14.609	0.0333
15	218.5083	+31.8982	13.734	0.0180
16	218.5445	+31.5823	14.420	0.0365