Color Index Analysis and Temperature Calibration of the High Amplitude

δ Scuti V2455 Cygni

Denzil Watts

A senior thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Bachelor of Science

Michael D. Joner, Advisors

Department of Physics and Astronomy

Brigham Young University

ABSTRACT

Color Index Analysis and Temperature Calibration of the High Amplitude
δ Scuti V2455 Cygni

Denzil Watts
Department of Physics and Astronomy, BYU
Bachelor of Science

New photometric data obtained at the West Mountain Observatory (WMO) and Apache Point Observatory (APO), along with spectral data from the Dominion Astrophysical Observatory (DAO), are presented for the high amplitude δ Scuti variable V2455 Cygni (V2455 Cyg). We present a color index analysis and calibrate the stellar temperature during the pulsation cycle based on these observations. Important to the temperature calibration was also preliminary period analysis to determine proper phasing of the light curve. Period analysis returned a fundamental frequency of 10.6150318 d^{-1} using 22 instances of maximum light. Using Hα and Hβ indices an effective temperature estimate of 7100 K to 8250 K was determined and then confirmed using intrinsic $B-V$ and $b-y$ indices. Reddening to calculate the intrinsic $B-V$ and $b-y$ indices was found by fitting the observed $B-V$ index temperature calculation to the Hα/Hβ temperature calculations to find E($B-V$) = 0.015. We then used the relation E($b-y$) = 0.74E($B-V$) to find E($b-y$) = 0.011. These intrinsic $B-V$ and $b-y$ color indices allowed us to classify V2455 Cyg as pulsating between A5 and F2 spectral classes. This estimate agrees with the estimated spectral class range and classification of V2455 Cyg as a high amplitude δ Scuti variable.

Keywords: color index, effective temperature, reddening, intrinsic magnitude

ACKNOWLEDGMENTS

I would like to thank the College of Physical and Mathematical Sciences at Brigham Young University for providing funding for mentored undergraduate research and also acknowledge the support of the BYU Department of Physics and Astronomy for continued research opportunities provided at the West Mountain Observatory. I am extremely grateful to my loving wife, Susan, who has been here to support me not only throughout schooling, but also with the writing of this thesis, being willing to proofread and shoulder my responsibilities while I have been busy. Lastly a special thanks to Dr. Michael Joner, who provided guidance and encouragement throughout the creation of this thesis and without whom this would not have been possible.

Contents

Chapter 1

Introduction

The classification of high amplitude δ Scuti variable stars (HADs) is that of pulsating variables that lie on the instability strip of the Hertzsprung-Russell (HR) diagram, an analysis of which is valuable as these stars provide excellent candidates for asteroseismology and the creation of models to understand stellar structure (Handler et al. 2009). (Yoss et al. 1991) presented the first published analysis of V2455 Cyg, in which the stellar classification of F2 was determined with a visual magnitude of V = 8.86 mag. This initial work also determined an absolute magnitude of M_V = 2.2, color index $(B-V)$ = 0.27, and space velocity S = 32 kms^{-1} at a distance of 215 pc. Further work was done by (Piquard et al. 2001) with V2455 Cyg being assigned the classification of a SX Phe variable with a period of P = 0.094206 days, which was then revised by (Wils et al. 2003) updating the classification of V2455 Cyg to a high amplitude δ Scuti star. (Wils et al. 2011) further refined work done on the period of V2455 Cyg with an updated ephemeris of Max = 2452885.399 + 0.094206008 x E. An effective temperature between 7200 K and 7900 K was determined by (Peña et al. 2019) using $uvby-\beta$ photometry with a determined surface gravity of log(g) from 3.6 to 3.9 and absolute visual magnitude in the range of 2.066 mag to 1.075 mag. The latest work (Ostadnezhad et al. 2020) determined the period to be slowly increasing, characteristic of most HADs (Breger 1990), with a fundamental frequency of 10.61574 d^{-1}. Our work seeks to build upon these past findings with an updated period analysis using $BV(RI)_C$ observations, but focuses primarily on color index analysis and temperature calibration using BV, by, and Hα/Hβ photometry and spectroscopy.

Chapter 2

Methods

2.1 Observations

Observations were made over the span of two years with $BV(RI)_C$ observations from the 0.3-m telescope at WMO and 0.5-m ARCSAT telescope at APO, *by* observations from the 0.3-m and 0.9-m telescopes at WMO, and Hα/Hβ photometric observations from the 0.9-m telescope at WMO and spectroscopic observations from the 1.2-m robotic telescope at DAO using the McKellar spectrograph. As a bright variable it was possible to collect large data sets of V2455 Cyg each night with observations of $BV(RI)_C$ having integration periods of less than 10 seconds and all other filters using integration periods in seconds within the range of double digits. Proper focusing and defocusing of the telescopes was necessary to ensure proper integration times for V2455 Cyg and also comparison stars in the field. Both photometric and spectroscopic data were reduced using the NOAO package of IRAF (Tody 1986). Photometric data was analyzed using both the apphot task of IRAF and AAVSO's VPHOT software. Spectroscopic data was analyzed using the sbands task contained within the onedspec task of IRAF.

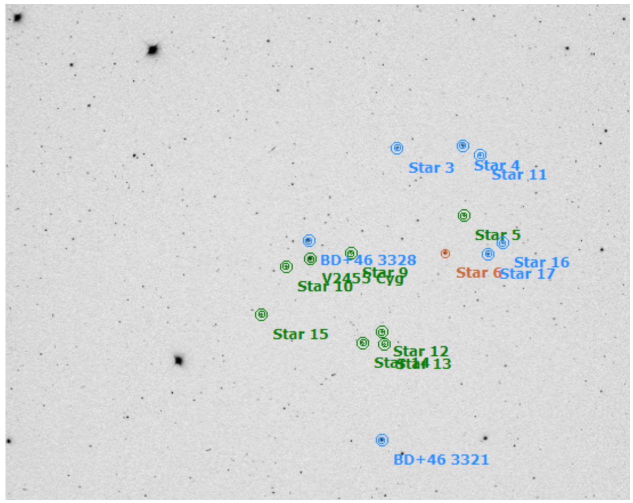

Figure 2.1 Above is shown the comparison stars used in the field of V2455 Cyg marked in blue with target stars such as V2455 Cyg marked in green. The VPHOT software requires a check star be selected as marked in orange. The field of view is 32.5’ x 26’ with up being east and right being north. This observation was made using the 0.3-m telescope at WMO using the *V* filter.

BD +46 3328 and several fainter stars, as shown in Figure 2.1, were chosen as comparison stars for V2455 Cyg. In the case of BD +46 3328 and BD +46 3321, *BV* magnitudes were assigned from the SIMBAD astronomical database (Wenger et al. 2000). The magnitudes of the comparison stars in other filters were determined using standard fields and derived transform equations. The Landolt standard field SA-110 was used for $BV(RI)_C$ transformations (Landolt 2009). Each night of *by* and Hα/Hβ observations was accompanied by observations of the open cluster NGC 752 in order to establish transformation equations using standard values for stars in the field from (Twarog et al. 2015) and (Joner & Hintz 2015). The approach for finding extinction coefficients for each night made use of the V2455 Cyg comparison stars and their airmasses, as these observations covered a large range of airmass. Transformations were created in the standard form of plotting extinction corrected observed standard field magnitudes against their published standard values for all standard field stars observed on a given night on the same graph, accounting for a respectably large range in color. We found minimal differences between a given filter’s transformation equations from night to night. It is noted that V and y published standard values are equivalent. We computed magnitudes in BV of BD +46 3328 and BD +46 3321 using transformation equations from SA-110 and found errors of .001 magnitudes.

2.2 Important Concepts

The primary concept important to this work is color indices, which are color values that are calculated by subtracting one observed filter measurement from another. Filters are designed to account for specific wavelength ranges of light and measure specific characteristics of a black body spectrum, mainly due to temperature differences. The systems used in this work are the Johnson-Cousins filter system, $BV(RI)_C$, the Strömgren system, *uvby*, and the the Hα/Hβ system, which involves narrow and wide passbands of Hα/Hβ absorption lines. If we compare one filter measurement to another, it is possible to obtain specific spectral characteristics for a source without having to do spectroscopy. Compared to photometry, spectroscopy returns highly specific spectral characteristics and has greater applications, but photometry can provide very accurate measurements for characteristics such as effective temperature, interstellar reddening, blanketing, surface gravity, and several others (Crawford 1987).

There are several key concepts to the effective temperature calibration of any stellar source. Sources need to be free from interstellar reddening, which is also known as interstellar extinction. This phenomena is caused by dust in the galaxy that scatter and absorb blue light but allow the transmission of red light. The scattering of the blue light leads to observed starlight being reddened in the higher intensity wavelengths of observed stellar spectra as it passes through dust and gas along the travel path to Earth. Reddening affects filters that focus on wide portions of the black body spectrum, such as the $BV(RI)_C$ and *uvby* systems. Conversely, filter systems that focus on specific absorption lines, such as Hα and Hβ, are considered reddening free as these produce indices focused on a difference in the absorption line. For example, the Hα passband filters share the same central wavelength and are thus identically reddened, making the resulting index reddening free. There are many methods that have been published on for determining reddening, but this work presents a simpler method as will be discussed in the analysis section, making use of the Hα and Hβ indices. The concept of reddening is directly tied to intrinsic magnitudes. These are magnitudes that have been corrected for interstellar reddening and must be computed in order to calculate correct effective temperatures (Carroll & Ostlie 2017).

Effective temperature calibration is also affected by blanketing. Blanketing is a direct effect of absorption lines on stellar spectra that primarily affects both blue and red regions of the spectrum as blanketing absorbs light at shorter wavelengths and raises the curve from what it would have otherwise been in the longer wavelengths (Athay 1972). Blanketing is important to recognize and affects filter systems with broader wavelength ranges. $BV(RI)_C$ is the most affected of the filter systems presented in this work, *uvby* was made with limiting blanketing in mind, and Hα/Hβ are free from the effects of blanketing.

Chapter 3

Results

3.1 Period Analysis

Period analysis was done using $BV(RI)_C$ data over 9 nights spread over 2 years using 22 observed times of maximum light. We found this to be significant as our analysis presents the largest collection of data used for period analysis on V2455 Cyg compared to published works. Period analysis was done using the program Period04 (Lenz & Breger 2005) returning a fundamental frequency of 10.6150318 d^{-1} and giving a period of 0.094206029(604) days, in contrast to the most recently published period of 0.094206044(14) in (Ostadnezhad et al. 2020). Along with the period we also determined an approximate semi-amplitude of 260 *mmag* and a phase of 0.102136. Comparison between the various filters returned similar results and we display the V and B phased curves in Figure 3.1. Future work will involve further period analysis with O-C diagrams and times of maximum light to present better refined results. It is important to note that period analysis is not the focus of this work, but finding the period and establishing an epoch were essential to this work in order to properly phase color indices and their respective calculated temperature ranges. We determined the epoch by assigning one time of maximum light as the reference epoch, HJD =

2460185.812. All observation times were compared to this reference epoch and period to determine the phase for each observation.

We found a notable spread at both the minimum and maximum sections of the *BV* phased data. The spread merits future investigation beyond the scope of our work presented here. For clarity on the curve we show in Figure 3.2 a *B* light curve from August 29, 2023. Each night presents symmetric curves but from night to night there is potential periodicity. For our purpose we used average minimum and maximum values from the phased data for our temperature analysis in both *B* and *V*, but did not find this necessary for *by* and Hα/Hβ data since those observations were taken in a much tighter time frame.

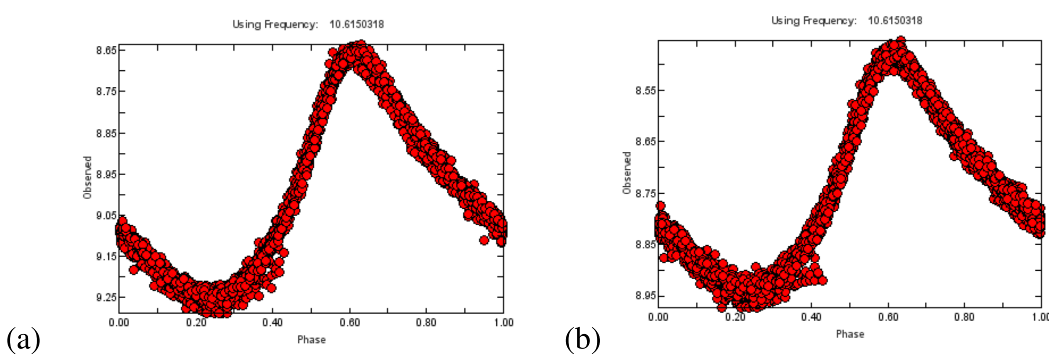

Figure 3.1 Above are the phased light curves of V2455 Cyg. The *B* phased data is shown in plot [a] and *V* phased data is shown in plot [b].

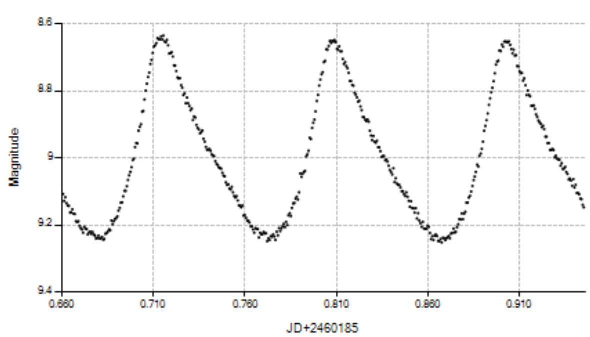

Figure 3.2 V2455 Cyg *B* filter light curve from August 29, 2023.

3.2 Hα and H β Indices and Temperature Analysis

Our work explores four color indices, $B-V$, $b-y$, Hα, and Hβ. The phased data from each color index we analyze in this work is presented in Figure 3.3. To calibrate the effective temperature of V2455 Cyg we primarily focused on the approach presented in (Joner & Hintz 2015) using the Hα and Hβ indices. These indices are calulated by subtracting wide passband Hα/Hβ observations from narrow passband Hα/Hβ observations respectively. These indices have proven themselves valuable in the calibration of stars as both indices are free from interstellar reddening or color excess, and also blanketing effects that influence other color indices. (Joner & Hintz 2015) present a direct relation between effective temperature and the Hα and Hβ indices using the relation θ = 5040/T_{eff}. This relation was found to be extremely accurate and found that V2455 Cyg itself fills the HR instability strip gap attributed to HADS variable stars. From these two relations we found a variation in effective temperature from 7100 K to 8250 K for Hβ and 7150 K to 8200 K for Hα, giving an error of approximately 50 K between the two indices.

A similar approach was taken in (Peña et al. 2019) using Hβ to determine a temperature calibration using a relation determined in (Rodriguez 1989) from (Petersen & Jørgensen 1972). We tried this approach for reference and found calculated values differing by 25 K compared to those published in (Peña et al. 2019), but we find the effective temperature relations found in (Joner & Hintz 2015) to be better refined, as we show with further color index temperature analysis.

3.3 $B-V$ and $b-y$ Indices and Temperature Analysis

In order to confirm our Hα and Hβ temperature calibration we compared these results to our $B-V$ and $b-y$ observations. To determine temperature from these indices we converted to intrinsic magnitudes by finding the reddening using a fitting process for our $B-V$ values. First we used the effective temperature relation from (Ballesteros 2012) to convert $B-V$ index values

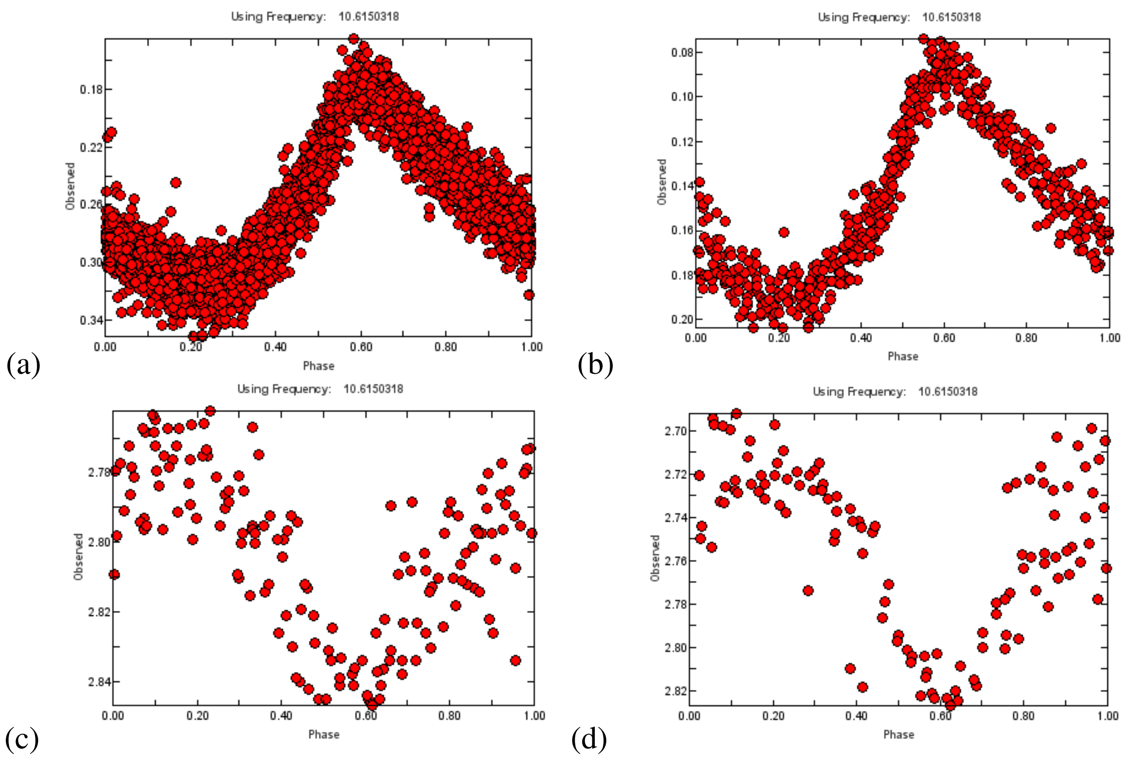

Figure 3.3 V2455 Cyg phased color index values with $B-V$ shown in plot (a), $b-y$ shown in plot (b), Hα in plot (c), and Hβ in plot (d). Note that for the $B-V$ and $b-y$ indices, lower values correspond with maximum brightness while the inverse is true for the Hα and Hβ indices.

into temperatures and then found the best fit for the resulting curve onto the calculated values determined from our Hα and Hβ calibration. We found a reddening coefficient of E($B-V$) = .015. To determine the E($b-y$) value, and also confirm our fit, a ratio of $E(b-y)/E(B-V)$ = 0.74 independently found in both (Crawford & Mandwewala 1976) and (Joner 1981) was used to determine E($b-y$) = .011, which we found to be in agreement with reddening found in (Peña et al. 2019).

In order to determine temperature from our calculated $(b-y)_0$ values we used the effective temperature relation found in (Napiwotzki et al. 1993) that also uses an approach built around θ = 5040/T$_{eff}$. With these relations and intrinsic values we found an effective temperature range for $B-V$ of 7110 K to 8280 K and an effective temperature range for $b-y$ of 7110 K to 8250 K.

From this we determined that the Hα and Hβ calibration is statistically significant, allowing us to conclude that the temperature calibration is accurate as 7100 K to 8250 K with an error range of 50 K. We show in Figure 3.4 the compared temperature curves from the various color index analyses. We hold to mainly the Hβ and $b-y$ color indices as Hβ is a trusted color index and $b-y$ contains less blanketing effects compared to $B-V$. We find the relationship between the Hα index and $B-V$ index interesting as they fit closely in a manner similar to our Hβ and $b-y$ indices.

As a final check, stellar classification and variation were also found using intrinsic $B-V$ and $b-y$ color indices. Table 1 shows the maximum and minimum determined intrinsic $B-V$ and $b-y$ values from the color index analysis. We determined that V2455 Cyg pulsates between A5 and F2 using determined color index values for those stellar classifications, $B-V$ from (Carroll & Ostlie 2017) and $b-y$ from (Palmer 1977). Using the stellar class range, rough temperature predictions from 7000 K to 8300 K can be made using the same publications. This range agrees with our range of 7100 K to 8250 K further supporting our final temperature calibration.

Table 1. $B-V$ and $b-y$ values

HJD	$(B-V)_0$ Max	$(B-V)_0$ Min	$(b-y)_0$ Max	$(b-y)_0$ Min
2460165	0.177	0.361		
2460182	0.175	0.352	0.081	0.208
2460185	0.161	0.333		
2460186			0.061	0.247
2460187			0.092	0.214

Note—Table 1 displays maximum and minimum intrinsic $B-V$ and $b-y$ values along with their corresponding HJD.

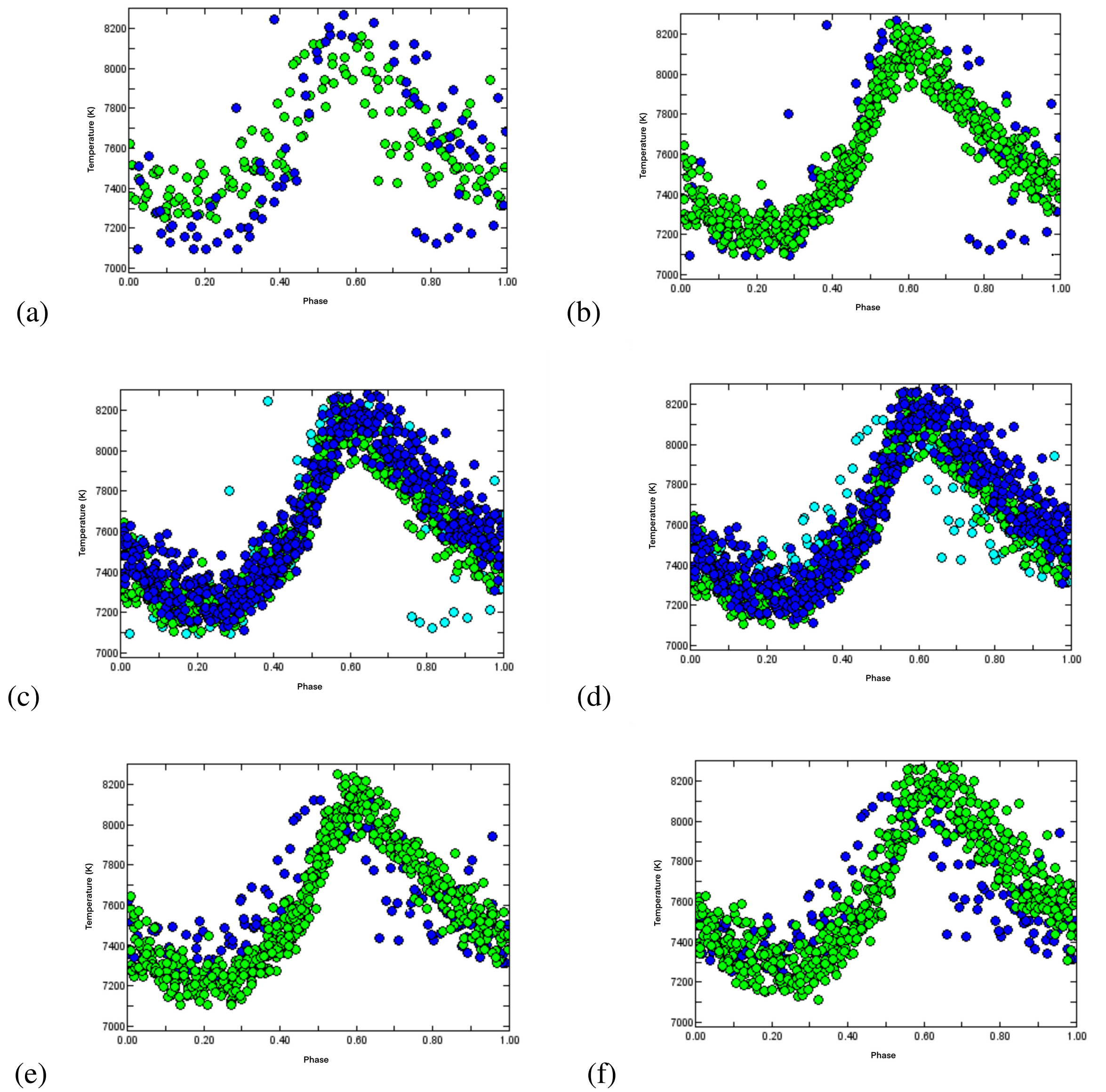

Figure 3.4 Phased temperature plots of V2455 Cygni with the x-axis as phase and y-axis as temperature with a range of 6975 K to 8300 K. Each graph provided above showcases the fit of the data by jointly plotting the temperature calibration of several color indices. Plot (a): Hα (green) plotted with Hβ (blue). Plot (b): Hβ (blue) plotted with $b-y$ (green). Plot (c): Hβ (light blue) plotted with $b-y$ (green) and $B-V$ (dark blue). Plot (d): Hα (light blue) plotted with $b-y$ (green) and $B-V$ (dark blue). Plot (e): Hα (blue) plotted with $b-y$ (green). Plot (f): Hα (blue) plotted with $B-V$ (green).

Chapter 4

Conclusion

In this work we conclude V2455 Cygni to have a fundamental frequency of 10.6150318 d^{-1} with a period of 0.094206029(604) days in relative agreement and building on previously published frequencies and periods. More work still needs to be done to properly analyze the period. With roughly 25 published instances of maximum light, using the times of maximum light over the past two years along with many yet to be analyzed nights, a comprehensive O-C diagram could be made and would build upon previous findings in the period changes of V2455 Cygni with time. Viewing our phased plots there appears to be periodicity in the maximum and minimum magnitudes, potentially caused by a companion star or some other factor, for which analysis would be extremely beneficial for the future calibration of other physical characteristics of this variable star.

This work has primarily determined an effective temperature range of 7100 K to 8250 K for V2455 Cygni using a variety of color indices to effective temperature relationships. Our strongest indicators are Hα and Hβ, as these measurements provide the most accurate indices and are further supported by our equivalent findings in both the $B-V$ and $b-y$ indices. Using fitting techniques we were able to determine the reddening of $B-V$ and $b-y$ to be E($B-V$) = .015 and E($b-y$) = .011, within proposed ranges of previous published works. This effective temperature range is also in agreement with the spectral class range of A5 to F2 we found for V2455 Cyg using both intrinsic $B-V$ and $b-y$ color indices. We still need to complete further analysis using $(V-R)_C$ and $(R-I)_C$ color indices to effective temperature relations to support findings.

This work also demonstrates the viability of published color index to effective temperature relations. We found that all relations used in this work fell into statistically significant agreement with an error of 50 K between color indices. Future work to create even more refined effective temperature relations using various color indices will greatly benefit works such as this to help streamline the analysis of high amplitude δ Scuti variable stars filling the HR instability strip gap. We are grateful for those who have pursued and published on these relations and are excited for all researchers actively pursuing new relations.

Bibliography

Athay, R. G. 1972, The Line Blanketing Effect (Dordrecht: Springer Netherlands), 202–236

Ballesteros, F. J. 2012, EPL (Europhysics Letters), 97, 34008

Breger, M. 1990, in Astronomical Society of the Pacific Conference Series, Vol. 11, Confrontation Between Stellar Pulsation and Evolution, ed. C. Cacciari & G. Clementini, 263–273

Carroll, B., & Ostlie, D. 2017, An Introduction to Modern Astrophysics, 2nd edn. (Cambridge, United Kingdom: Cambridge University Press)

Crawford, D. L. 1987, in New Generation Small Telescopes, 345–350

Crawford, D. L., & Mandwewala, N. 1976, Publications of the Astronomical Society of the Pacific, 88, 917

Handler, G., Guzik, J. A., & Bradley, P. A. 2009, in AIP Conference Proceedings (AIP)

Joner, M. D. 1981, Master Thesis, Brigham Young University, Provo, U.T.

Joner, M. D., & Hintz, E. G. 2015, The Astronomical Journal, 150, 204

Landolt, A. U. 2009, AJ, 137, 4186

Lenz, P., & Breger, M. 2005, Communications in Asteroseismology, 146, 53

Napiwotzki, R., Schoenberner, D., & Wenske, V. 1993, A&A, 268, 653

Ostadnezhad, S., Forozani, G., & Ghanaatian, M. 2020, Research in Astronomy and Astrophysics, 20, 105

Palmer, L. 1977, AJ, 82, 158

Peña, J. H., Rentería, A., Villarreal, C., & Piña, D. S. 2019, Rev. Mexicana Astron. Astrofis., 55, 193

Petersen, J. O., & Jørgensen, H. E. 1972, A&A, 17, 367

Piquard, S., Halbwachs, J. L., Fabricius, C., Geckeler, R., Soubiran, C., & Wicenec, A. 2001, A&A, 373, 576

Rodriguez, E. 1989, PhD Thesis, University of Granada, Granada, Spain

Tody, D. 1986, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 627, Instrumentation in astronomy VI, ed. D. L. Crawford, 733

Twarog, B. A., Anthony-Twarog, B. J., Deliyannis, C. P., & Thomas, D. T. 2015, The Astronomical Journal, 150, 134

Wenger, M., et al. 2000, A&AS, 143, 9

Wils, P., van Cauteren, P., & Lampens, P. 2003, Information Bulletin on Variable Stars, 5475, 1

Wils, P., et al. 2011, Information Bulletin on Variable Stars, 5977, 1

Yoss, K. M., Bell, D. J., & Detweiler, H. L. 1991, AJ, 102, 975