PHOTOMETRIC AND SPECTROSCOPIC TIME-SERIES OF THREE δ SCUTI VARIABLES

by

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ABSTRACT

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Senior Thesis

Included is the analysis of photometric and spectroscopic observations of the δ Scuti variables V873 Herculus and V2455 Cygni, and spectroscopic observations of δ Scuti. Using the methods of Crawford (1958) , we found H_β and H_α indices for these stars and plotted them versus time. These spectroscopic time-series were then compared to the photometric data and phased using periods determined from the photometric data. We first used δ Scuti ($V_{mag} = 4.71$) as a bright test star and found that this method would indeed give us the desired variability. After this confirmation, we moved to two dimmer stars, V873 Her ($V_{mag} = 8.40$) and V2455 Cyg ($V_{mag} = 8.53$) and found that the temperature curves were almost, but not exactly, in phase with the luminosity curves. This implies that the star is radially pulsating and could, in the future, give insight into the amplitude of pulsation, effective radius of the photosphere, or some other valuable characteristic of the star.

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Chapter 1

Introduction

The Brigham Young University Astronomy research group has been studying δ Scuti variables for a number of years. The research group has been involved in the search for variable stars, the classification of variable stars, and the determination of the periods of variable stars. To accomplish these things it is oftentimes necessary to secure two types of data: photometric and spectroscopic. The photometric data is usually used to analyze the period of the star, where the spectroscopic data is usually used to determine the spectral type of the star as well as determine radial and rotational velocities. Since the star's overall temperature varies over time, we have the unique opportunity to use the spectroscopic data in conjunction with the photometric data to further understand the period of the star. Our goal in this study is to determine if this can be done and if comparing the two types of data will give more information about the star.

1.1 δ Scuti Variables

A δ Scuti variable is a radially pulsating star that lies in the instability strip and is in the main-sequence stage of its evolution. These stars tend to be relatively hot and are of spectral type A or F. These stars pulsate due to an instability in their interiors known as the κ *mechanism* that was introduced by Arthur Eddington in 1925.

1.1.1 The κ Mechanism and the Instability Strip

The κ mechanism describes a process in which the star varies slightly from hydrostatic equilibrium which results in the compression of a layer of the interior. Due to this compression the opacity of the layer increases and the amount of energy absorbed by that layer is more than it normally would be. This results in an overshoot of equilibrium during the resulting expansion. When the layer expands the opacity decreases and it absorbs less energy than it normally would, causing another overshoot of equilibrium during the compression. This process continues resulting in a sinusoidal radial pulsation of the star.

The main difficulty that Eddington had with the κ mechanism is that when a layer of the star contracts, it generally increases in temperature which *decreases* the opacity rather than increases it. If this is indeed the case, the κ mechanism would have no chance of causing the pulsation of the star. This issue was resolved by assuming that the instability occurs at a layer that is near an appropriate temperature to ionize either hydrogen or helium. In this case, rather than the temperature increasing, the excess energy from compression goes into ionizing the respective element. The temperature remains very close to the same for this layer, and the opacity will increase as needed to cause pulsation.

The actual position of this ionization layer of the star leads to certain limits in which the pulsation can occur. For example, if the star is large and very hot, the ionization layers will occur fairly close to the surface. In this case, the pulsating layer will only drive a very small part of the star to radially pulsate, and the pulsations will be quickly damped out. On the other hand, if the star is very small, the ionization layer will occur very far into the interior of the star and the pulsation will not have enough force to drive the outer layers of the star.

Also, these pulsations can only occur in layers of the star that are transferring energy to the surface through the process of radiation. If the layer is transferring energy through convection, the pulsation can not occur. In small stars, convection becomes much more common, to the point that in very small stars, there are no radiative layers at all in the star.

Both of these effects give rise to an upper and lower temperature limit for which the κ mechanism will drive pulsations in a star. The temperatures at which this can occur define a strip on the H-R diagram that is known as the *instability* *strip*. If a star at any given evolutionary period moves into the instability strip, it will begin to have radial pulsations. δ Scuti stars are those main sequence stars that fall into this strip.

1.1.2 Changing Luminosity and Temperature on the Surface

When the luminosity and temperature of a star are measured, it is the surface at which they are measured. Due to the κ mechanism, the surface of the star is pulsating in and out. When the star expands, the temperature decreases and when it contracts, the temperature increases. The overall luminosity can be described by the following equation where L is the luminosity, R is the radius, σ is the Stefan-Boltzmann constant, and T is the temperature.

$$L = 4\pi R^2 \sigma T^4 \tag{1.1}$$

The luminosity equation tells us that the luminosity of a star changes based on the radius and temperature. So, while the star is contracting and the temperature is increasing, the overall luminosity of the star increases as well. As the star expands and the temperature decreases, the overall luminosity of the star decreases. If we made a chart of the luminosity vs. time and temperature vs. time for a pulsating star, these two curves should have peaks and valleys at nearly the same time.

δ Scuti variable stars pulsate due to an instability in their lower layers as described above. The study of these stars generally involves studying the period and amplitude of pulsation. This is done by looking at how the luminosity changes as the star pulsates. The science of measuring the amount of light coming from a source is called *photometry*.

1.2 Photometry

To perform photometry, we need something to capture the light from a star. The most crucial tool in doing this is the telescope. Telescopes are designed to capture as much light as possible in the shortest amount of time. Telescopes capture light and then focus it onto some sort of detector. In modern astronomy, the detector of choice is primarily a *charge coupled device* (CCD hereafter). A CCD is essentially a grid of wells that captures electrons. When light comes in as photons from the sky, it hits a metal plate on the CCD which emits electrons through a process called the photoelectric effect. The electrons that are emitted by the plate are then captured by the CCD and the number of electrons in each well are counted. An image is created based on this count where a large number of electrons captured corresponds to a large number of incoming photons from a bright object, like a star. A star will make a circle shape on a CCD that covers many pixels, covering more if the seeing conditions for the night are less than ideal. In doing research on variable stars, it is best to do this process multiple times to take many images over a period of time.

To get quantifiable information from these images, we use a technique called aperture photometry. An aperture, in this case, is a circle that we place around an area of interest, and we count all the electrons on the CCD in that area. The amount of electrons corresponds to the number of incoming photons, so we call the count of electrons divided by the exposure time of the image, the flux. Flux is a measure of photons per second and is used in the following equation to calculate the magnitude of the star where f is the flux, m_{inst} is the instrumental magnitude and *zeropoint* is an arbitrarily chosen offset.

$$m_{inst} = -2.5log_{10}(f) + zeropoint \tag{1.2}$$

It is important to note that, based on this equation, the higher the number m is, the smaller the number f is. This means that the magnitude scale is backwards from most other scales in that the star with the smallest magnitude is the most luminous star.

Another important aspect of photometry is the use of filters. A star emits light at all wavelengths, but more light at some wavelengths than others. The photoelectric

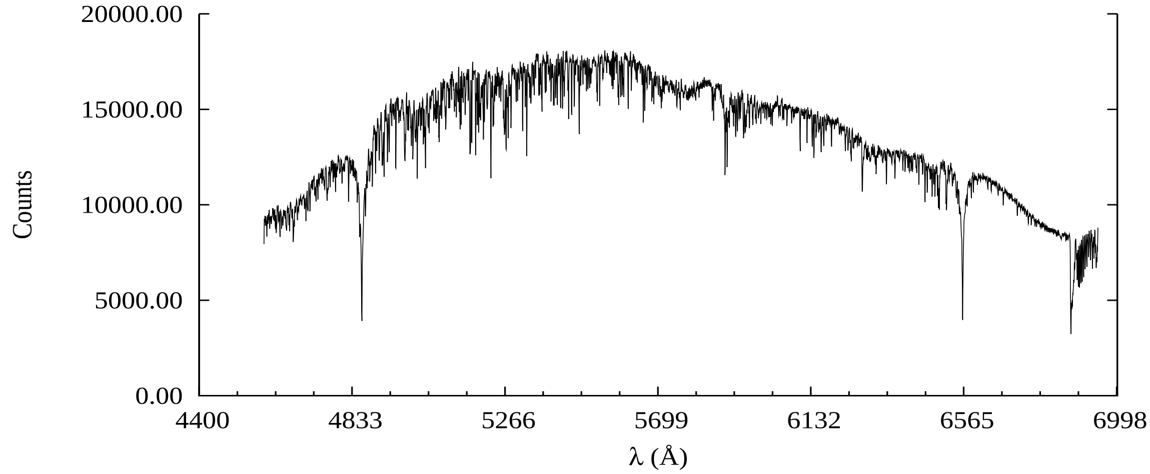

Figure 1.1: The spectrum of δ Scuti created with *splot*.

effect that occurs on the CCD does not distinguish between different wavelengths of light. In order to distinguish between different wavelengths, a filter is inserted in front of the detector. A filter only allows certain wavelengths to pass through, for example, a B filter allows light in the blue end of the spectrum, a V filter allows light in the green area of the spectrum, an R filter allows light in the red end of the spectrum, and so on for many different filters. This allows astronomers to know how much light comes at each of the wavelengths and can give insight into the temperature of the star.

1.3 Spectroscopy

Spectroscopy is the study of the spectrum of incoming light. A spectrum is created by passing incoming light through a prism or grating which will separate the light by wavelength. The result is that we have a line of light where each part of the line represents a different wavelength. We capture the spectrum of a star the same way mentioned previously, with a CCD camera. The image can then be analyzed by plotting the strength of the light along the dispersion axis, to get a plot like the one shown in Figure 1.1. This new image consists of a continuum and, in the case of stars, absorption lines. The continuum is the standard line of the spectrum, the line that exists where there are no absorption lines. Absorption lines occur at distinct wavelengths that indicate the chemical makeup of the star as well as the temperature. To better explain this, we are going to take a step back into the physics of spectral features.

An atom consists of a nucleus that contains protons and neutrons, and a set of electrons that are orbiting the nucleus. These electrons can be in different orbits around the nucleus based on their energy. These orbits are quantized, or occur in steps. An electron can transition from one energy level to another, but to do so, must either emit a photon, when going to a lower level, or absorb a photon when going to a higher level. Since the energy levels occur in discrete steps, the energy absorbed or emitted by the electron is specific to the transition between levels. The energy of a photon is directly related to its wavelength according to the following relation where λ is wavelength, c is the speed of light, h is Planck's constant, and E is the energy:

$$E = hc/\lambda \tag{1.3}$$

Since the energy of the photons absorbed or emitted is quantized, so also is the wavelength. This means that every element has a specific set of photon wavelengths that its electrons can absorb or emit. The pattern of these wavelengths has been well studied in a laboratory setting, and can be used to identify the chemical composition of incoming light.

Stars emit light because they are hot. The core of a star emits light at all wavelengths, though it emits more at some wavelengths than others. The emitted light passes through the atmosphere of the star before it can be captured by our telescopes. The atmosphere of the star is colder than the core, and so light coming from the core excites electrons in the atmosphere to higher energy levels. Since the energy levels are discrete as described above, only certain wavelengths of light are absorbed. When we look at the spectrum of a star, we see that at certain wavelengths there are very few incoming photons, because those are the wavelengths at which absorption occurred in the atmosphere of the star. These are the absorption lines mentioned earlier. Different stars have different sets of absorption lines; they are catalogued and then used to separate stars into categories called spectral types. The spectral types are: $OBAFGKM$, with the O stars being the hottest and the M stars being the coolest. Here we see that the presence or absence of spectral features corresponds with temperature.

The temperature of a star determines the spectral features that will appear in the star. The rules are not straightforward and will not be discussed in entirety in this paper. The important thing to know is that the stars of type A and F have very deep lines in the optical part of the spectrum. These lines result from the transition of electrons in hydrogen atoms to and from the n=2 energy level. Lines that transition to and from this level are called Balmer lines and are labeled with Greek letters. The line that results from the transition from the n=3 level to the n=2 level is called the Balmer α line, or more simply the H_α line. The line that results from the transition from the n=4 level to the n=2 level is called the Balmer β line, or the H_β line. These two lines occur at wavelengths 6563 Angstroms(Å) and 4861Å respectively.

Within an individual spectral type, the strength of the lines can vary based on temperature. To measure this, a filter, like the ones described for use in photometry, can be placed before the detector that will filter out light that is not at these specific wavelengths. Filters that have maximum transmission at the wavelengths of Balmer lines are referred to as H_α and H_β filters. Using the technique described in Crawford (1958), we can use two filters that are both centered at the same wavelength, one wide and one narrow, and create a temperature index based entirely on the amount of light coming from these absorption lines. This temperature index can then be calibrated to tell us the approximate temperature of the star. The process of using a spectrum to calculate magnitudes in different filters is called spectrophotometry. The details of how this process was used in this study is described in Section 3.2.4.

1.4 δ Scuti

Three δ Scuti variable stars were studied for this paper: δ Scuti, V873 Herculis, and V2455 Cygni. The first of these three, δ Scuti is, in fact, the prototype for the whole classification of stars, hence the classification being named after this star. It is a 4.5 mag star of spectral type A8. Templeton et. al. (1997) report a period for this star of 5.160769 cycles d^{-1}. In this study, we used spectroscopic observations of δ Scuti as a test of our method. Because the star is fairly bright, it was a good first benchmark of our ability to see temperature variation in the spectrum. Based on the successful results of these observations, we were able to move to other stars that were considerably dimmer, but which were the main focus of our study.

1.5 V873 Herculis

V873 Herculis is a 8.39 mag δ Scuti variable of spectral type F0. It was first discovered to be variable by Aluigi et. al. (1994) in which they reported four times of maximum light and two possible pulsation periods of 7.91 cycles d^{-1} and 7.77 cycles^{-1}. Further photometric observations were reported in Hintz & Schoonmaker (2009) where 24 more times of maximum light were found and a corrected period of pulsation of 7.863608 cycles d^{-1} was found. We have extended the baseline of those observations to include another 18 nights of photometric data that include ten new times of maximum light in the 2009 season as well as 6 nights of medium-dispersion spectroscopic data taken at the Dominion Astrophysical Observatory 1.2-m telescope. We report ten new times of maximum light and report a corrected pulsation period of 7.863894 cycles d^{-1}. The spectroscopic data taken on V873 Herculis shows a sinusoidal temperature variation as expected and lies slightly out of phase with the photometric data.

1.6 V2455 Cygni

The final star observed in this study is V2455 Cygni. This star was first suspected to be variable by Yoss et. al. (1991) and further study performed by Piquard (2001) and Wils et. al. (2003) confirm its classification as a high amplitude δ Scuti variable with a period of 10.615035 cycles d^{-1}. This star varies drastically in brightness ranging from 8.5 mag to 8.9 mag. The photometric data showed very clean light curves and nine new times of maximum light were found and added to the current set in Wils et. al. (2003) and Wils et. al. (2009). A corrected pulsation period of 10.603233 cycles d^{-1} was found which slightly modifies the one reported in Wils et. al. (2003). The spectroscopic data taken on V2455 Cygni also shows a periodic temperature variation that lies slightly out of phase with the photometric data.

Chapter 2

Observations

2.1 Photometric Observations

Photometric data of V873 Her and V2455 Cyg was taken on two telescopes, the 0.4-m David Derrick Telescope at the Orson Pratt Observatory(hereafter, OPO), located on BYU campus, and the 0.3-m telescope at BYU's West Mountain Observatory(hereafter, WMO). A variety of combinations of CCDs and focuses were used at the OPO for the observations. A summary of these combinations can be found in Table 2.1. At the WMO, a focal ratio of f/9 was used at the Cassegrain focus. Using an ST-10 CCD which has a pixel size of 6.8μm, the telescope gave a plate scale of 0.49"pixel^{-1}. For V873 Her, 18 nights of photometric data was collected which provided 10 new times of maximum light. For V2455 Cyg, 7 nights of photometric data was collected which provided 9 new times of maximum light.

2.2 Spectroscopic Observations

All spectroscopic data was taken on Dominion Astrophysical Observatory's 1.2-m McKellar Telescope during four runs throughout the summers of 2008 and 2009. Spectra were centered at 5710Å exactly between the H_α (6563Å) and H_β (4861Å) spectral lines. The observations were taken with the spectrograph mounted at the Coudé

Table 2.1. Telescope and CCD Specifications for the 0.4m DDT

Telescope	CCD	Pixel Size (μm)	Plate Scale ("pixel^{-1})	Array Size (pixel)	Years
Cassegrain	Apogee Ap8p	24	0.98	1024x1024	2002
Newtonian	Meade Pictor 1616XTE	9	1.14	1536x1024	2002
Cassegrain	SBIG ST-1001	24	0.98	1024x1024	2005
Newtonian	SBIG St-10	6.8	0.86	2184x1472	2007-2009

Table 2.2. Spectroscopic Observations

Date	Star Oberved	Number of Hours Observed
July 7, 2008	δ Scuti	2.93
May 21, 2008	V873 Her	5.05
May 22, 2008	V873 Her	5.20
June 20, 2009	V873 Her	4.43
June 22, 2009	V873 Her	3.20
June 23, 2009	V873 Her	3.93
July 3, 2009	V873 Her	5.75
July 4, 2009	V2455 Cyg	6.03
July 5, 2009	V2455 Cyg	3.82
July 6, 2009	V2455 Cyg	6.35
July 7, 2009	V2455 Cyg	4.12

focus using a grating of 300 grooves mm^{-1}, blazed at 4200Å to yield a dispersion of 40.9Åm^{-1}. The SITe4 CCD was used, which has 15 micron pixels on a 4096 x 2048 pixel chip.

During these four runs, one night of data was taken of δ Scuti, six nights of data was taken of V873 Her, and four nights of data was taken of V2455 Cyg. Each of these nights included only calibration frames, standard stars and the respective variable. The purpose of the observations was to observe the variable for as long as possible in one night in order to see the H_β index change over time. As such, the star was observed constantly for many hours. A summary of the observing times is given in Table 2.2.

Chapter 3

The Process of Reduction and Analysis

3.1 Photometric Data

All of the photometric data obtained for this study was processed using standard reduction packages in the Image Reduction and Analysis Facility (IRAF). IRAF contains many packages which, in turn, contain programs that can be used to take raw data from the telescope, and prepare it for analysis. The reduction of photometric data starts with basic corrections to the information contained in the image header. From there, calibration frames are applied to correct for inconsistencies across the CCD as well as other unfavorable conditions. Finally, aperture photometry is performed on the frames to obtain instrumental magnitudes of the stars. The resulting data is then plugged into $MicrosoftExcel$, where the analysis of the data is conducted. A program named $Period04$ (Lenz & Breger 2004) is also used for period determination. This section will detail the whole process from start to finish.

3.1.1 Naming and Header Correction

When the data is downloaded from the telescope it is in a raw form. This means it has had no corrections done to it. The data is in the form of images which have a header embedded in them. The header gives important information about the image, including the time observed, the observer, the observatory, the type of frame, the exposure length, etc. Much of this information will be used later on in the reduction process since the programs in IRAF often refer to information in the header to do their various tasks. Some of the information found in the header is incomplete or not in the format that IRAF will use, and some important information, such as the airmass, the coordinates of the star, and the epoch is missing. To correct these issues we turn to the *astutil* package in IRAF.

We used two programs in this package, the first is *hedit* and the second is *asthedit*. *hedit* simply edits the header of a specified file. It will ask for the field to be edited as well as the value to enter in that field. If the specified field is not present, *hedit* will simply add it to the bottom of the header. *asthedit* uses a file with a ".cmds" extension and performs *hedit* for each of the fields specified in the cmds file.

To have the files ready for further reduction the following changes should usually be made. First, the "filetyp" field must be set correctly. For zero frames, it is set to "Bias" and should be changed to "zero". For dark frames it is set to "Dark" and should be changed to "dark," and for flat frames it is set to "Flat" and should be changed to "flat." Note that some of these changes only change the case of the first letter, but IRAF distinguishes between upper and lower case letters, so the correct case must be used. The next step is to either change or add the field "filter" to the flat frames. The value of the field should reflect the filter that the flat frames were taken in, for this study "V". Also, each frame that has a filter should have a subset affiliated with it, so for the frames taken in the V filter, the "subset" field should be set to "V". The next step is to run *asthedit* on all the object frames to change all of fields specified in the cmds file.

After the headers have been edited, two more programs need to be run: *setjd* and *setairmass*. *Setjd* is a program that accesses information in the header about the observation time of the frame as well as the epoch and location of the observatory. Using this information, it adds the Heliocentric Julian Date (HJD hereafter) into the header under the field marked "hjd". This information will be used extensively when plotting the luminosity of the star against time. The second program, *setairmass*, will use the coordinates of the star observed, and with the observatory location and the time observed, will calculate the airmass and add it to the headers. These two programs should be run on the object frames after they have had their headers corrected with *asthedit*.

One of the benefits of IRAF is that a user can write a program and call it from the IRAF command line. To make all the editing of headers more simple, I wrote two programs entitled *opoheaders* and *wmoheaders* to quickly do these corrections. They are specific to images taken from the OPO and the WMO respectively , but a derivation of the script could easily be made for any observatory. See Appendix A for the complete code of these programs.

The final step before moving on is to change the file type of the images and appropriately name them. To do this we use the IRAF program called *rfits*. *Rfits* will convert all selected images into the default IRAF filetype and will name these files based on user input. Oftentimes, the data coming from observatories has inconvenient filenames to work with, and this is the opportunity to change them. The program changes all selected files to the appropriate filetype and then assigns them a filename with a numbered extension, starting with "0001." For example, for all the zero frames, we specify the name "zero," and *rfits* assigns the names "zero0001.fits," "zero0002.fits," etc. As a note for anyone who may, in the future, use IRAF, my suggestion is to make all the filenames as simple as possible, since it is likely they will need to be typed repeatedly.

3.1.2 Applying Calibration Frames

Once the headers are completed and the files are the correct file type, the next step in the reduction process is the application of calibration frames. To eliminate as much noise as possible, we apply three calibration images to our objects frames: zeros, darks, and flats. See Figure 3.1 for an example of each of these frames. A *zero* is a frame that is exposed for zero seconds. These frames account for any electrons that are left in the pixels of the CCD despite not being exposed to the light. Each pixel has a different zero level, and for each pixel, these will be subtracted from the images. A *dark* is taken to account for the fact that there is a current running through the detector. Electrons from this current can end up in the pixels and create an inaccurate reading of the amount of light from a star. A dark is exposed for about

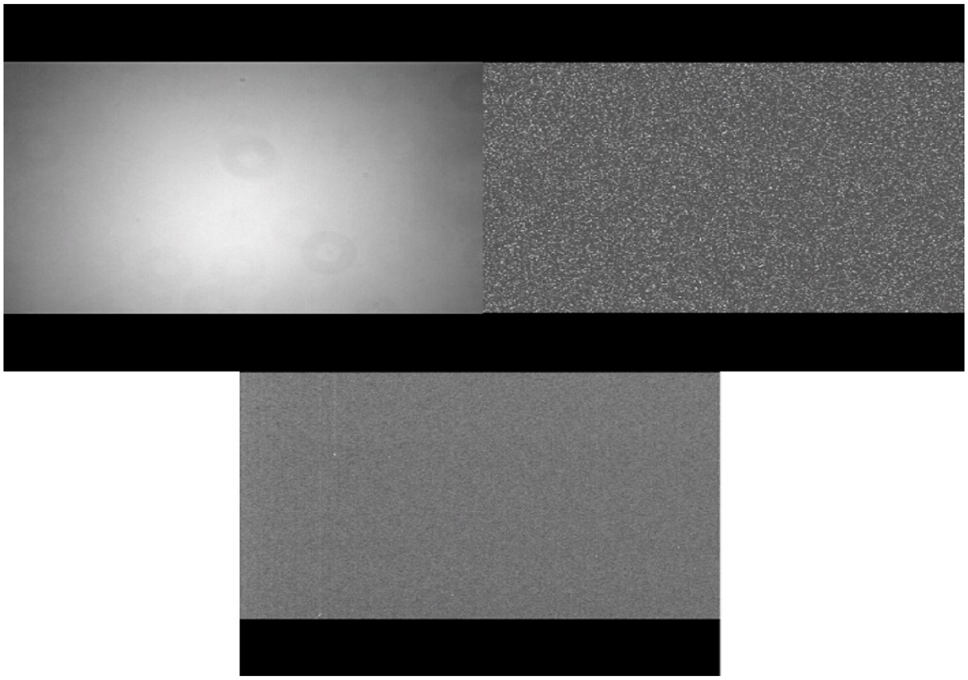

Figure 3.1: The three calibration frames that are applied. Top left: flat; top right: dark; bottom: zero;

the same time as the object frames are, but with the shutter closed, so none of the resulting electrons come from a celestial object. On telescopes that run very cold, there is very little "dark current," but on the DDT and the 0.3-m at WMO, this is not the case, so this dark current is also subtracted from the image. A *flat* is taken to correct the problem that each pixel of the CCD responds slightly different when light is shined on it. Flats are taken of the sky where there is the same brightness across the whole field of view. This is best done at dusk or dawn. These flats will be scaled to one and then divided off of the object frames.

To make these corrections we use the IRAF package CCDRED, which contains a number of programs to help in the reduction of CCD frames. The programs we will use are: *zerocombine*, *darkcombine*, *flatcombine*, and *ccdproc*. *zerocombine* will combine all the zeros , into a single "master zero." This combined zero will be used to calibrate all future frames. *darkcombine* performs two tasks, first it runs *ccdproc*

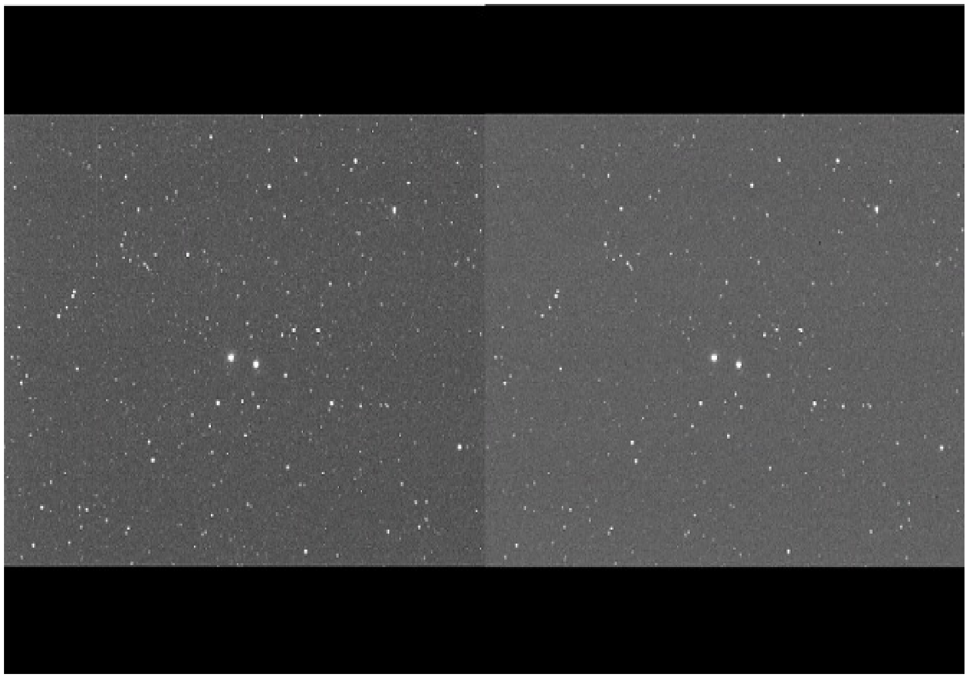

Figure 3.2: To the left is a raw image of V2455 Cygni, to the right is the processed version of the image

on all the darks, applying the zero calibration to each, and then combines the frames into a "master dark." *flatcombine* also performs two tasks, first it runs *ccdproc* on all the flats, applying the zero and dark calibration to each, and then combines the frames into a "master flat." The parameters of the program can be tweaked so that if a user is working in multiple filters, it will combine the flats by the "subset" field of the header. Finally, we use *ccdproc* on the object frames to apply the zero, dark, and flat calibration. Again, if the correct parameters are selected, this can be done based on the "subset" field of the header. After this program is run, we see a significant improvement of the quality of the object frames. See Figure 3.2 for an example of the raw and processed object frames.

3.1.3 Preparing an Image for Photometry

Once the object images have had the calibration frames applied, we can begin to retrieve data from them. Since we will be using the technique of differential photometry, we will be finding photometric data on many of the stars in the field. To do this we will use the *phot* program in the *apphot* package of IRAF. To run *phot*, we must first make a coordinate file that contains the positions of the stars of interest. To do this, we will display one of our frames in the $DS9$ imaging program. To select a star to add to the coordinate file, we simply click on the star and a circle will appear around it. A broad magnitude range of stars should be selected if possible, and stars should be selected close to the center, since the CCD response turns non-linear near the edges. Once the stars are marked, the coordinates are saved as a "ds9.reg" file in the same folder as the object frames. To prepare for photometry, we also take the opportunity to quickly look through the object frames to see if there are ones that need to be removed. This can be done manually or by using a program, such as *ap_imagecheck*, a script that is part of the Swenson-Iverson Data Reduction Package (SIDAP) that is fully described in Swenson (2008). Also, if the telescope has flipped over the pier to continue taking data late into the night, some frames may need to be rotated. This can be done by either rotating your coordinate file, or rotating the images themselves. SIDAP also contains a program for this entitled *ap_rotate*(Swenson 2008).

3.1.4 Nightphot4

$Nightphot4$ is a program written at BYU to assist in doing photometry. It will correct for changing seeing conditions through the night as well as automatically adjust coordinates from frame to frame. See Appendix B for the full code of this program. $Nightphot4$ begins by running the IRAF program $psfmeasure$. This program allows you to measure the average $point - spreadfunction$ (PSF) of the stars on the frame and outputs the average full-width at half-maximum (FWHM) of the stars.

This is re-entered into the program and is used to adjust the size of the aperture. If seeing conditions get worse through the night, the PSF will widen, increasing the FWHM, which in turn increases the size of the aperture. This means that the ideal aperture size is always used, based on the current conditions of the sky. Once it has the aperture size, *nightphot*4 will run the IRAF program *phot* to perform photometry on the selected stars. This program counts the number of photons within the aperture as well as the number of photons in a small annulus within the aperture. The number of counts in the annulus, called the sky-count, is multiplied by the number of pixels in the aperture then subtracted from the total number of counts. This is divided by the length of the exposure and gives the number of counts from the star per second of exposure time. This is considered the flux of the star and is converted to instrumental magnitude using a specified zeropoint, in our case 20.0, according to the following equation:

$$m_{inst} = -2.5log_{10}(f) + zeropoint \tag{3.1}$$

Phot outputs the instrumental magnitude of each star selected into a file with a .mag.1 extension. *Nightphot*4 then brings up the next frame and repeats the process over again for all the object frames selected. When all the frames have been "photted," *NightPhot*4 will output a .lst file to you that contain a list of the star number, instrumental magnitude, observation time, airmass, and filter of all the object frames.

3.1.5 Varstar5

*Varstar*5 is another program written at BYU for the purpose of easily performing differential photometry. *Varstar*5 requires, as input, a list identical to the one that is output by *Nightphot*4 that contains the star number, instrumental magnitude, observation time, airmass, and filter for each observation. The process of differential photometry is to, first, build an ensemble of stars in the field whose average magnitude is relatively stable, and then compare the magnitude of the stars in the field to this ensemble. Using the input list, $Varstar5$ automates this process. It displays a short list of all the observed stars, the difference between their average magnitude and the average magnitude of the stars contained in the ensemble, and the overall error per observation of this differential magnitude. The program then allows for the removal of stars from the ensemble that have high errors, and recomputes using the new set of stars. This process is repeated until a satisfactory ensemble is built and then outputs a list the contains the observation time and the differential magnitude for each star.

3.1.6 Changing from Instrumental to Apparent Magnitude

Once the variable star has been compared to a stable ensemble, we move out of IRAF and into *Excel* for magnitude correction and period analysis. With our data input into *Excel* we want to convert our instrumental magnitudes, which were calculated using an arbitrary zeropoint, into an apparent magnitude. To do this, we look for the published apparent magnitudes for the stars in our ensemble. The Hubble Guide Star Catalog 2.3 (Lasker et. al. 2006) contains many of the needed magnitudes in the V filter. These magnitudes are subtracted from the differential magnitudes of the ensemble stars, and the results are averaged. This average is the correction for the night and is added to the instrumental magnitudes found in $Varstar5$ to give the apparent magnitude of each observation. The apparent magnitudes can then be plotted by their observation time, and we have a plot called a *lightcurve*. See Figure 3.3 as an example.

3.1.7 Period Determination and Phasing Data

All the work on the photometric data up to now has been preparation for the analysis. We now have the information in a format that can be used to determine the period. The first step in this analysis is to calculate all the $times\ of\ maximum$

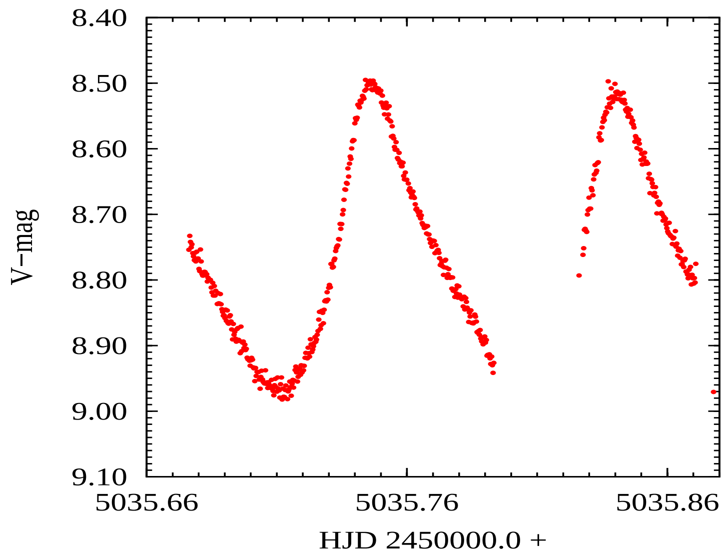

Figure 3.3: A photometric light curve of V2455 Cyg

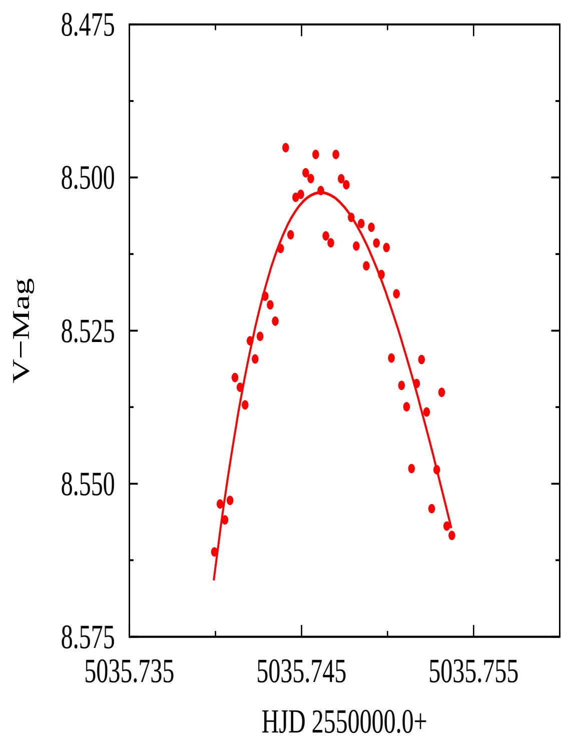

Figure 3.4: An example of fitting a 3^{rd} order polynomial to find the time of maximum light

light in our data set. This is the moment in the pulsation cycle of the star when the star is at its brightest. This is accomplished by having *Excel* fit a 3^{rd} order polynomial to the peak a light curve and display the equation. Figure 3.4 shows one of the peaks of the light curve shown in Figure 3.3 and the polynomial fit to it. We then calculate the derivative of this equation and numerically calculate where it crosses the x-axis. The time when the derivative is zero is the time of maximum light. Once all the times of maximum light have been calculated, the first can be chosen as cycle zero. The time elapsed is then be calculated for each later time of maximum light by simply subtracting the zero time from it. Next, we divide the time elapsed by an approximated period. This period could be determined graphically from the data, be one given in a previous publication, or be a period found using *Period*04 which will be discussed soon. The result of this computation is a number where the integer is the cycle number and the decimal is the phase. From one maximum to the next is one cycle, and the fraction of the period that the star has gone through at a certain observation time is the phase. For the initial period determination, the important part of this number is the cycle number, so the decimal for each number can be subtracted off. If the cycle number is plotted versus the time of maximum light, the slope of the resulting line is the period of the star.

*Period*04 is a program designed to run a *fast fourier transform* (FFT hereafter) on a set of data and report the primary periods of pulsation. The program is simple to use, a data file containing a list of magnitudes and HJDs is imported into the program, and then the program is asked to calculate periods. It performs and FFT and spits out the primary pulsation period of the star. The error for the calculation is shown and then, this pulsation period can be removed from the data. The residual pulsation periods can then be calculated the same as the primary. For this study, only at the primary pulsation period, further overtones are reported in Hintz & Schoonmaker (2009).

With the period in hand we can phase the data and produce an O-C diagram. Phasing the data is especially helpful if some of the nights of data were not taken

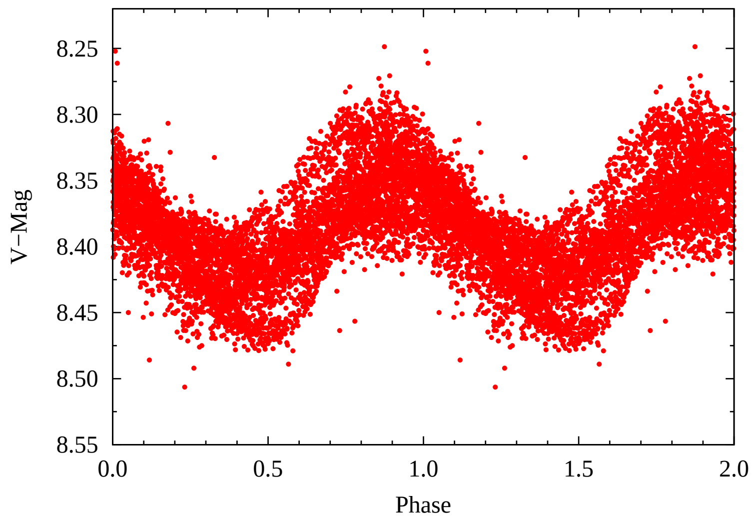

Figure 3.5: The photometric data of V873 Her in a phase plot

for a full period. By phasing the data, these observations can contribute to the overall understanding of the star. Phasing the data is simple: for each observation, we calculate the elapsed HJD from some zero time and then divide the result by the period we determined. The integer part of this number can be subtracted off so that only the decimal part, or phase information, is left. This number will be between zero and one for all the observations and can be plotted against the apparent magnitude to produce a graph like the one shown in Figure 3.5. Next, we can determine whether or not the period is changing over time. This is accomplished by making an plot of the observed time of maximum light versus the calculated time of maximum light. This type of plot is referred to as an $O - C$ *diagram*.

Figure 3.6 as an example of one of these diagrams. We observed a set of time of maximum light and used them to calculate the period, but if the period is changing over time, then a non-changing period used to calculate the times of maximum light from some zero time will give slightly different results than were observed. So, we multiply the period determined earlier with the cycle number of the time of maximum light and then add the zero time to the result. The time that comes out of this

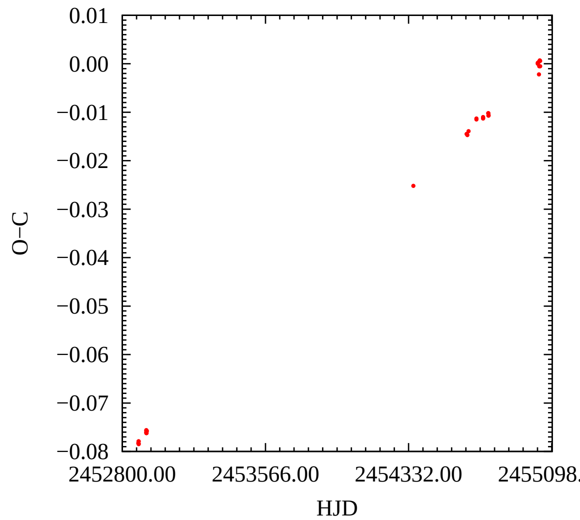

Figure 3.6: The O-C diagram for V2455 Cyg

calculation is the calculated time of maximum light. We then subtract this number from the observed time of maximum light for the same cycle and repeat for each of the times of maximum light in our data set. These differences can then be plotted against the observed time. *Excel* can then fit 2^{nd} order polynomial to the data, and the x^2 term of this equation describes rate of period change. If this number is large enough to be statistically significant, it implies that something, like a binary companion, could be making the period change.

From this point, other information could also be gleaned from the photometric data, but for this study, we will turn our attention to the spectroscopic data.

3.2 Spectroscopic Data

The spectroscopic data for this study was reduced using reduction tools in IRAF. The spectra start in the same form as the photometric data: images taken on a CCD. The difference is that these images are much narrower and the spectrum of the star has been projected across the length of the image. To get a good look at these spectra, we use the IRAF command *splot*, which takes a slice of the image one pixel wide and plots the intensity at each pixel.

From raw spectra, we correct the headers of the spectra and appropriately name them. Next, we apply calibration images and trim the ends off the spectra. The process of reduction is slightly different, particularly in the fact that there is no *dark* taken for spectroscopy. Since the telescope runs at very low temperatures the dark current is negligible and is ignored. When looking at spectra, cosmic rays are commonly a problem and are removed as much as possible. Also, we run a program that collapses the spectra down to one-dimension and uses comparison frames, called *arcs*, to calibrate the pixels to wavelength. Spectral features in these wavelength-calibrated spectra are then measured by artificially introducing a filter function. The results are calibrated to standard stars and analyzed for period information.

3.2.1 Header Correction and Naming

Spectroscopic data, like the photometric data, consists of images with attached headers. The headers are exactly the same as the ones discussed previously, and are treated the same. The "imagetyp" field of the header needs to be changed for the zeros, flats, object frames and arcs. The arcs should have the value "comp" in this field, since they are "comparison" frames. The arcs also need to have the field "epoch" added to the header so that the observation time can be calculated later. The *asthedit* command should be performed on the object frames, the *setjd* command should be performed on the object frames and the arcs, and the *setairmass* command should be performed on the object frames.

Once the headers have been corrected we perform the *rfits* command on the files and name them appropriately for later use. It is important to note that the default file type for IRAF should be set to ".imh" rather than ".fits" for reducing spectra, as the programs work better when the spectra are in the ".imh" format.

3.2.2 Applying Calibration Frames and Cosmic Ray Removal

To apply the two calibration frames, the zero and flat, we use a slightly different approach than we did for the photometric data. One important difference is that the spectra are not always the same size as the calibration frames and both are trimmed to match in size. The images can be trimmed when using *ccdproc*. The process begins with the zeros being trimmed and then combined using *zerocombine*. These are then applied to the flats at the same time they are trimmed using the *ccdproc* command. The flats are then combined together using $flatcombine$. Here we have another deviation from the photometric data. The width of the image on the CCD of the flat field is often smaller than the width of the object images. The counts of the flats are divided out, so if the counts are between zero and one, it increases rather than decreases the number of counts on the object frame when they are divided out. Also, the flat generally has a distinct curve to it since the CCD is more responsive in the red than the blue. To correct both of these issues, we run another program on the flats them called $apflatten$. This program finds the position of the actual flat exposure on the CCD and sets all other pixels to the value one, so when they are divided out, they do not change the data. Also, this program allows you to find a function to fit the flat that will be taken out of the object images. This removes the distinct curve due to the non-linear response. For this study, a 9^{th} order SPLINE3 function was used to correct the flats. $Apflatten$ produces a new flat image which is used for calibration. Finally, the object frames are trimmed and have the flat and zero applied to them to remove all the noise.

The last correction that needs to be made to the data is to remove any cosmic ray hits. Cosmic rays can drastically affect the data if they hit near one of the spectral features that we are observing. IRAF has a tool that will remove them appropriately titled *cosmicrays*. Running this program with the default parameters usually removes the worst of the cosmic rays hits.

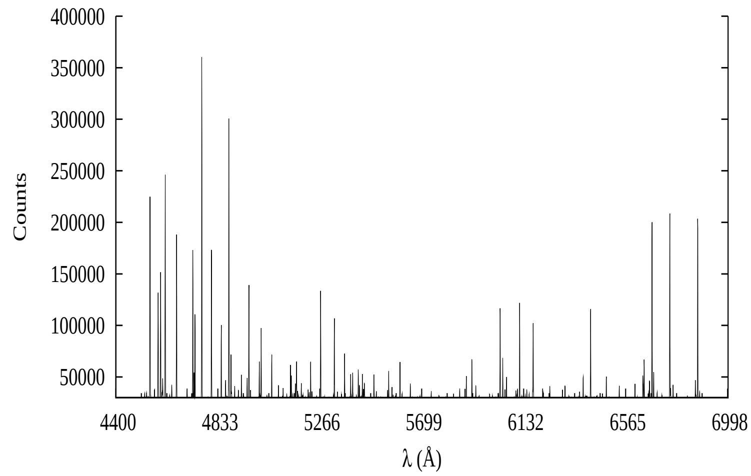

Figure 3.7: The Spectrum of an FeAr arclamp used for wavelength calibration

3.2.3 Wavelength Calibration

Once the calibration frames have been applied and the cosmic rays removed, we are ready to wavelength calibrate our spectra. When the spectra are plotted using *splot*, the x-axis is labeled by the pixel number, and we need it to be labeled by the wavelength. That way we can have IRAF analyze multiple spectra that may be shifted with respect to each other but will have the same spectral features at the same wavelength. This wavelength calibration is accomplished by a program called *doslit*. This program uses the comparison frames, the arcs, to do the calibration. Arcs are images taken of lamps, in our case iron-argon lamps, that have well documented spectral features. Using a published map of spectral features for the lamp, we identify the spectral features on our arc, and tell the program what wavelength they are located at. See Figure 3.7 for the spectrum of an FeAr arclamp. After marking all the spectral features of the arc, the program calculates a function that describe how the wavelength changes across the pixels. With this relation, *doslit* applies the function to our object frames and the spectra becomes calibrated by wavelength instead of

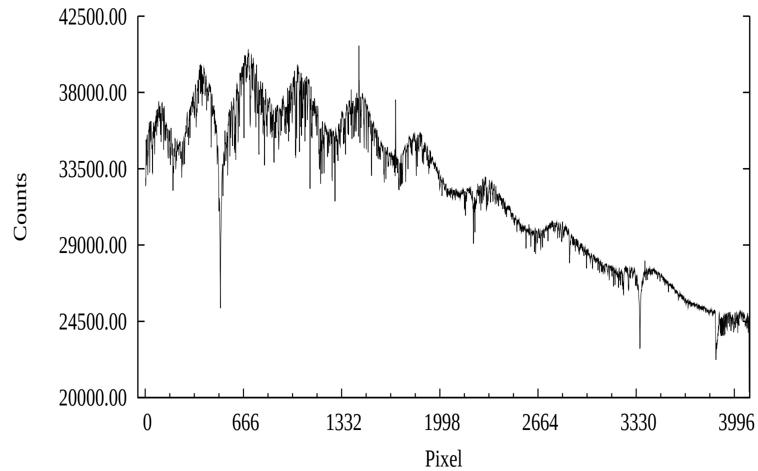

Figure 3.8: A raw spectrum of δ Scuti

pixel. Also, *doslit* collapses the width of the spectrum to one pixel by combining the overall intensity of the star together, so we now have a single spectrum, one pixel wide, that contains all of the star's information and is labeled by wavelength. Figures 3.8 and 3.9 show a spectrum before and after the reduction process.

3.2.4 Spectrophotometry

Using the wavelength-calibrated one-dimensional spectra that *doslit* outputs, we can begin to measure the strength of the spectral features. For this study, we are interested in the H_α line and the H_β line. The method that we use is outlined in Crawford (1958) where we define two filters, a wide and a narrow for each line, and center them both at the same wavelength. Because they are both centered at the same wavelength, we have created a reddening-free index. The magnitude is recorded through both the wide and narrow filters, and the difference is taken. This tells us the difference in the line strength and the strength of the surrounding continuum and is referred to as the H_β or H_α index, depending on which of the lines the filters

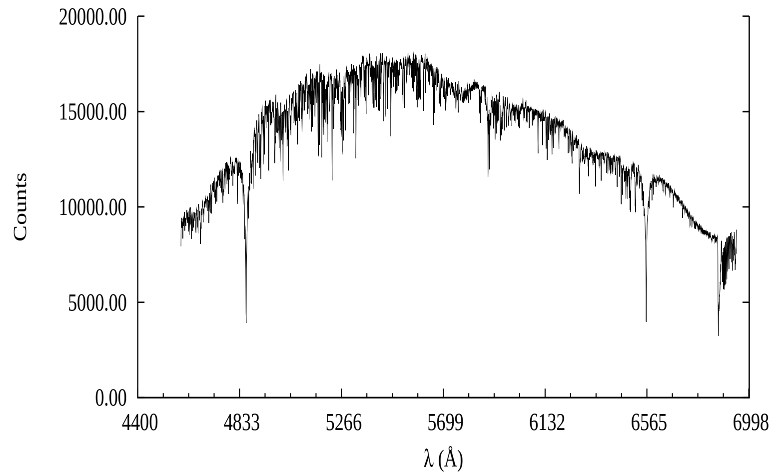

Figure 3.9: A reduced spectrum of δ Scuti, ready for analysis

were centered on. One of the most convenient things about using computers for this project is that this index can be measured artificially. IRAF contains a program called *sbands* that artificially adds a filter to the data and measures the magnitude through that filter. An input file is made that tells *sbands* the wavelength of the center of the filter, the width of the filter, the name of the filter, and the shape of the filter function. The program then convolves the filter onto the spectra and measures the magnitude through that filter. Figures 3.10 and 3.11 show the H_α and H_β filters used in this study. Since this filter was not physically present at the time of observation, this measurement can be done many times with different filter functions at different wavelengths very quickly. *Sbands* outputs a file that gives us the indices for each of the spectra that is input into *Excel* for further examination.

3.2.5 Standardizing Data

Like the photometric data, the index that *sbands* provides is based off of an arbitrary zeropoint, so the indices must be calibrated to actual values using standard

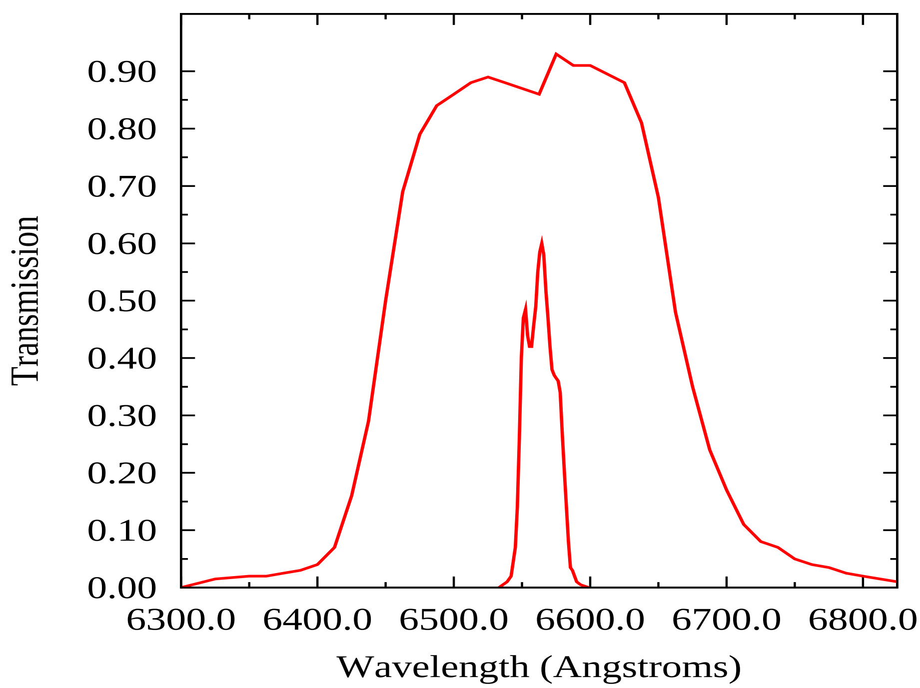

Figure 3.10: The wide and narrow H_α filters used in this study.

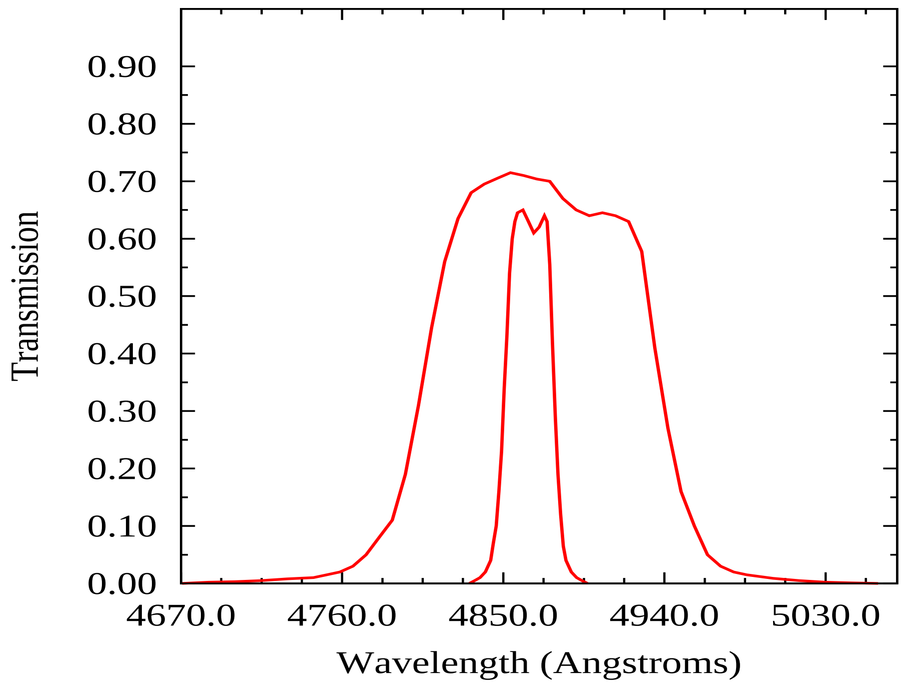

Figure 3.11: The wide and narrow H_β filters used in this study.

stars. Unlike photometry, however, this is a more complicated process. First, the standard stars must be reduced exactly the same way as the regular stars, must be wavelength calibrated, and must be analyzed using *sbands*. Each standard generally has two or three observations done on it, and we average these out so we have a single index for each standard star. For this study, the published H_α and H_β values for these stars are taken from Adams (2009) and Taylor & Joner (1992) respectively. A plot is made where the observed index is plotted against the published value. The equation of the resulting line gives us the correct adjustment. The observed index of our star is put in as the x value, and the equation gives us the y value, which is the corrected value.

3.2.6 Phasing Data

The corrected indices can then be plotted against their observation time to see if there is any variability. Using the same method described above, all of the data points gathered can be phased using a determined period. From here, we can compare the spectroscopic light curve with the photometric light curve. The photometric curve describes the luminosity of the star where the spectroscopic light curve describes the temperature of the star and the hope is that some correlation between the photometric and spectroscopic data can be determined. If the data does appear to be in phase, it means that cause of the luminosity change is also the cause of the temperature change. A pulsation of the outer atmosphere would cause both of these quantities to vary periodically and would confirm our current model of a δ Scuti variable as a pulsating star.

Chapter 4

Results

4.1 δ Scuti

The time-series spectroscopic observations taken on δ Scuti show that it is indeed possible for our method of observation to work. The resulting graphs show the kind of variability we expect to see in the temperature index of a pulsating variable star. These graphs are shown in Figure 4.1 Both the H_α and H_β indices by almost three hundredths. This is a fairly small amount of variation to see even considering the high luminosity of the star. After seeing this variation, we continued our analysis by using *sbands* to apply a Stömgren b and y filter. Using the resulting values, we were able to graph a time-series of a $(b-y)$ index to compare to the previous indices. This graph showed some significant abnormalities. This tells us that different ends of the spectrum were being affected differently by the atmosphere over the course of these observations indicating that our night of observations was a non-photometric night, and the favorable results that we obtained were possible under less-than-perfect observing conditions. Since the observations of δ Sct were simply aimed at testing the capability of our instruments and data analysis methods in obtaining temperature information, and that test proved favorable, we shifted our focus from δ Sct to the higher magnitude stars in which we are significantly more interested.

4.2 V873 Herculis

4.2.1 Photometirc Results

The photometric observations of δ Scuti built on the results of Hintz & Schoonmaker (2009). We report 10 new times of maximum light and a refined period. Times of maximum light from Aluigi et. al. (1994), Hintz & Schoonmaker (2009), and this

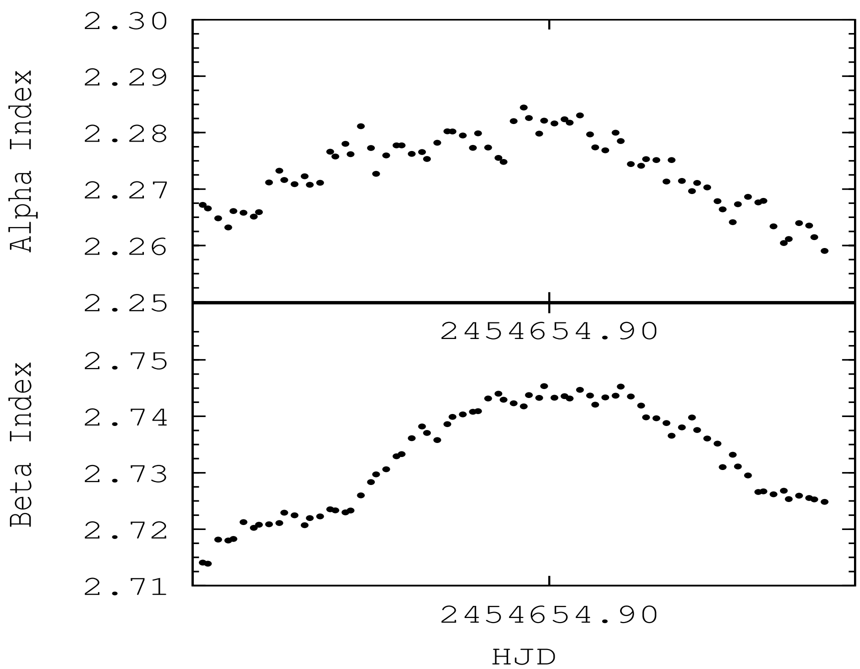

Figure 4.1: The H_α and H_β time-series for the spectroscopic data of δ Sct

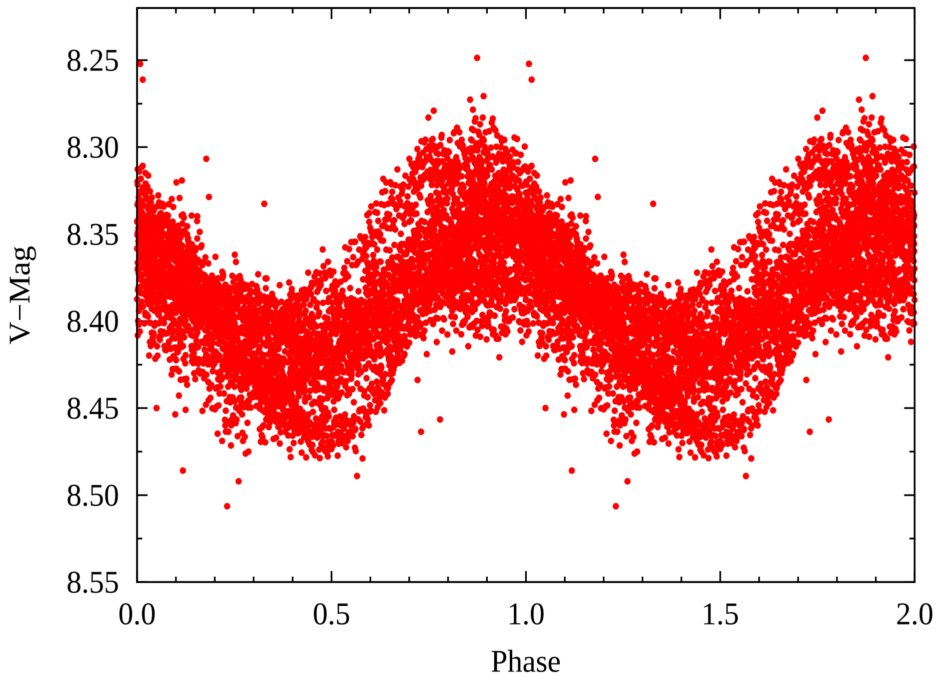

Figure 4.2: All nights of photometry on V873 Her phased with a period of 0.12716924 d^{-1}

paper are shown in Table 4.1. Beginning with the period of 0.12716809 d provided in Hintz & Schoonmaker (2009), we found cycle numbers for each of the times of maximum light and then ran a *LINEST* function in *Excel* on the results. Using the times of maximum light and the new period found from the this function, we report the following ephemeris for V873 Her:

$$HJD_{max} = 2454968.8222(5) + 0.12716924(66)E \tag{4.1}$$

Figure 4.3 shows the $(O - C)$ diagram for all 34 times of maximum light. In each season, there is a fairly wide range of $O - C$ values which is a result of the multi-periodic nature of the star. Hintz & Schoonmaker (2009) gives a much more in-depth analysis of the first few harmonics of pulsation in the star which is beyond the scope of this study. This multi-periodicity can also be seen in the phase diagram

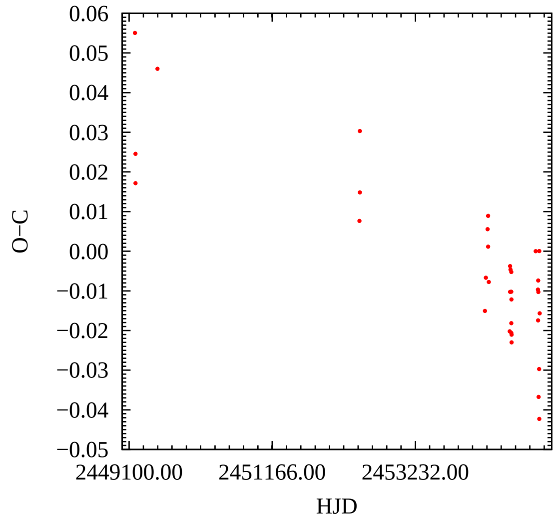

Figure 4.3: The O-C diagram for V873 Her

of the photometric data. Figure 4.2 shows all 19 nights of photometry phased with the given ephemeris.

The spectroscopic observations of V873 Her provided us with temperature indices across long time runs. Individually, these nights did not always look to be varying with the photometric data, but when phased with the ephemeris given above, the sinusoidal nature is obvious. These two curves both have some error in them that is likely due to the multi-periodicity of the star, but the basic curve is apparent as seen in Figure 4.4 . It is even more obvious when the spectroscopic data is lined up next to the photometric data, and their x-axes are lined up exactly. In this orientation, we see that the phase at which we observe the highest temperature is very close to the phase at which we see the highest luminosity. Since the luminosity is most strongly dependent on the temperature, this is the result that we expect. We also expect to see a slight difference in phase due to the dependence of the luminosity on the radius. Since the star has its highest temperature at its smallest radius, these two values will fight for dominance in luminosity and the temperature will win, but not without the radius causing a shift in phase from the luminosity. Using *Period*04 we attempted to

Table 4.1. Times of Maximum Light for V873 Herculis

Cycle	HJD 2400000.0+	O-C
-45486	49184.4572	0.0551
-45431	49191.4210	0.0245
-45430	49191.5408	0.0172
-42922	49510.5101	0.0460
-20005	52424.8092	0.0076
-19958	52430.9205	0.0303
-19957	54236.8210	0.0148
-5756	54236.8210	-0.0151
-5646	54250.8180	-0.0067
-5450	54275.7554	0.0056
-5403	54281.7357	0.0089
-5402	54281.8551	0.0011
-5324	54291.7654	-0.0078
-2949	54593.7799	-0.0202
-2902	54599.7733	-0.0038
-2901	54599.8940	-0.0102
-2862	54604.8592	-0.0046
-2768	54616.8125	-0.0052
-2767	54616.9347	-0.0102
-2760	54617.8145	-0.0206
-2759	54617.9441	-0.0182
-2752	54618.8403	-0.0122
-2737	54620.7370	-0.0230
-2736	54620.8661	-0.0211
0	54968.8222	0.0000
267	55002.7667	-0.0097
275	55003.7763	-0.0174
290	55005.6939	-0.0074
306	55007.7257	-0.0103
338	55011.7687	-0.0367
393	55018.7700	-0.0297
408	55020.7073	0.0001
416	55021.6823	-0.0423
456	55026.7957	-0.0157

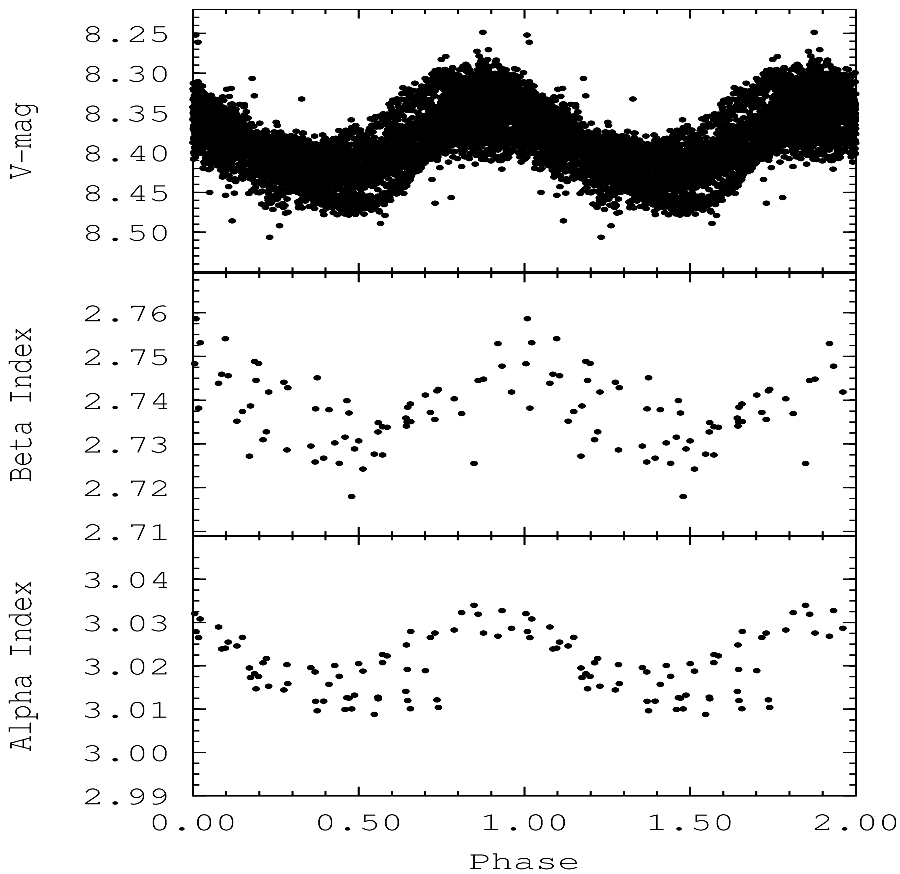

Figure 4.4: At the top, the photometric data; in the middle, the H_β indices; on the bottom, the H_α indices. All plots were phased with a period of 0.12716924 d^{-1}

find the difference in phase between the temperature and luminosity, but due to the multi-periodicity, we were unable to acquire any satisfactory result. Overall, though, our study was a success in showing that the temperature curve very closely follows the luminosity curve.

4.3 V2455 Cygni

4.3.1 Photometric Results

The photometric observations of V2455 Cyg indicate that it is a high-amplitude δ Scuti variable. The data shows that the amplitude of its pulsation in the V filter is approximately 0.5 magnitude, a large number compared to the 0.15 magnitude amplitude of V873 Her. We report 8 new times of maximum light in addition to those given in Wils et. al. (2003) and Wils et. al. (2009) which are all shown in Table **??**. Using these times of maximum light and our refined period from *Excel*, we report the following ephemeris for V2455 Cyg:

$$HJD_{max} = 2455022.8400(5) + 0.09420259(7)E \tag{4.2}$$

Using this ephemeris, we have created a phase diagram showing all of the photometric data points plotted with V-mag vs. Phase, shown in Figure 4.5. In making this plot we have noticed that the different nights of data show what appears to be different offsets in magnitude. Also, comparing the data taken with the 0.4-m DDT compared with the data taken at BYU's WMO, we find that the data taken on campus has much more error associated with it than the data taken at WMO. While their are benefits in seeing at the WMO, this fact should not account for the difference in quality of the data. The source of this error is unknown, and for the moment is keeping this data from being quantitatively useable. However, despite these errors, we are able to get the basic information about the star that we need, specifically, the period and the phase plot shown above. The purpose of this study is not to give a full photometric analysis of V2455 Cyg, but to show that it is possible to compare the temperature and luminosity curves of the star to compare their relative phases. We are continuing to take observations of V2455 Cyg and hope to publish the results sometime in the near future.

Table 4.2. Times of Maximum Light for V2455 Cygni

Cycle	HJD 2400000.0+	O-C
-22689	52885.3991	-0.0783
-22668	52887.3778	-0.0779
-22667	52887.4720	-0.0779
-22666	52887.5656	-0.0785
-22665	52887.6599	-0.0784
-22234	52928.2634	-0.0762
-22233	52928.3582	-0.0756
-22232	52928.4520	-0.0760
-22222	52929.3940	-0.0760
-22221	52929.4885	-0.0757
-22220	52929.5823	-0.0762
-22200	52931.4667	-0.0758
-7062	54357.5561	-0.0252
-4038	54642.4354	-0.0145
-4037	54642.5296	-0.0145
-3995	54646.4860	-0.0147
-3931	54652.5157	-0.0139 .
-3486	54694.4383	-0.0115
-3485	54694.5327	-0.0113
-3105	54730.3298	-0.0112
-3104	54730.4239	-0.0113
-3102	54730.6126	-0.0110
-2807	54758.4031	-0.0102
-2806	54758.4973	-0.0102
-2797	54759.3447	-0.0107
-2796	54759.4389	-0.0107
-2795	54759.5332	-0.0106
0	55022.8400	0.0000
1	55022.9344	0.0002
65	55028.9636	0.0004
73	55029.7146	-0.0022
84	55030.7525	-0.0005
116	55033.7682	0.0007
137	55035.7464	0.0006
138	55034.8395	-0.0005

Table 4.3. Phase Differences Between Different Time-Series on V2455 Cygni

	HJD	seconds
Photo-Alpha	0.01641	133.5549 .
Photo-Beta	0.02118	172.3866
Alpha-Beta	0.00471	38.3818

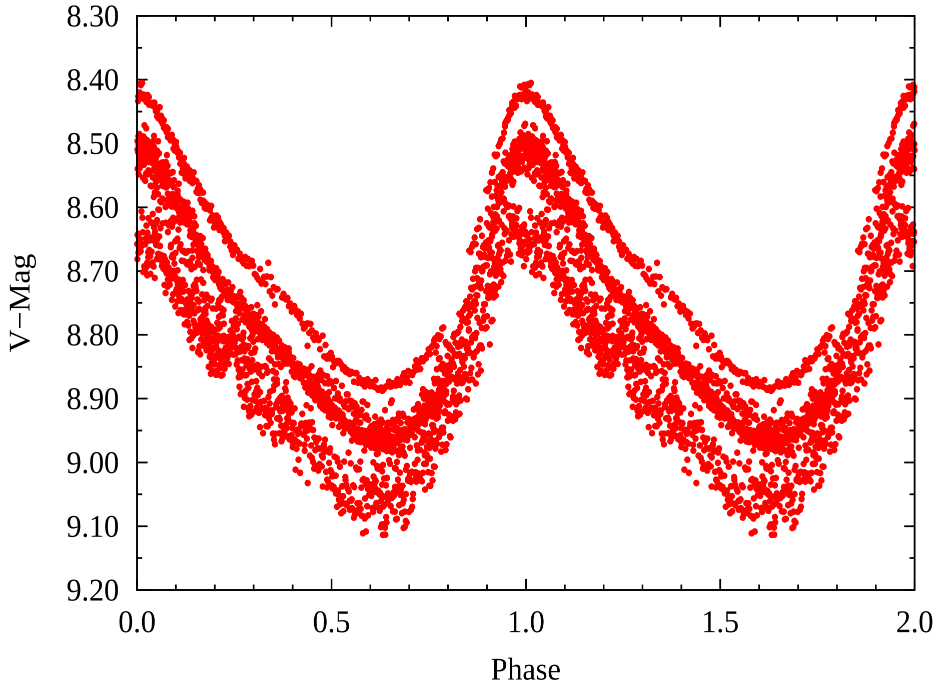

Figure 4.5: All nights of photometry on V2455 Cyg phased with a period of 0.09420259 d^{-1}

4.3.2 Spectroscopic Results

The spectroscopic observations of V2455 Cyg, like our previous star, show the temperature indices varying sinusoidally across long time runs. When phased with the ephemeris given above we find that the time of maximum luminosity closely corresponds to the time of maximum temperature as can be seen in Figure 4.6. We see a larger variation in the temperature index than we saw with V873 Her which makes sense since we have a larger difference in luminosity. Also, current observations of V2455 Cyg show that the pulsation is dominated by a single period rather than multiple ones like V873 Her. Because of this, we can more clearly see the variation in the temperature index over time. Also, it allows us to use *Period*04 to find the phase difference between these curves. Table 4.3 reports the results. Another interesting feature to note is that not only the phase of the luminosity and temperature curves similar, but the actual shapes of the curves are similar. V2455 Cyg has a very characteristic short rise and long fall that is also seen in the temperature curve, which reinforces that the variations seen are coming from the same source.

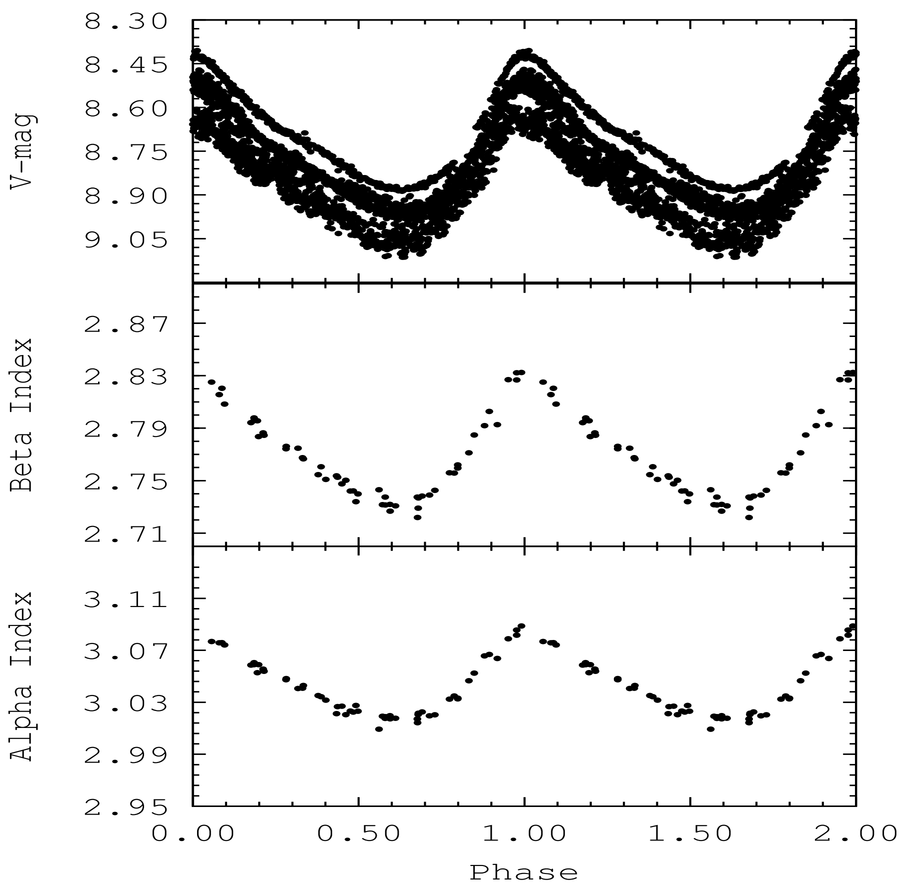

Figure 4.6: At the top, the photometric data; in the middle, the H_β indices; on the bottom, the H_α indices. All plots were phased with a period of 0.09420259 d^{-1}

Chapter 5

Conclusions

The purpose of this study was to observe the spectroscopic temperature indices varying over time in a manner similar to the luminosity curve. To do this we used spectroscopic and photometric data on variable stars taken from the 1.2-m telescope at DAO and the telescopes at the OPO and WMO. From the data on δ Scuti, we have found that using the given telescopes, we can observe the temperature varying as a function of time. After looking at the photometric and spectroscopic data of our other stars, V873 Herculis and V2455 Cygni, we can see that the temperature varies with a period similar to that of the luminosity and that these two curves are close, but not exactly, in phase.

Along with these observations, we report new times of maximum light for both V873 Her and V2455 Cyg, as well as refined periods of 0.12716924(66) d and 0.0942028(20) d, respectively. Hintz & Schoonmaker (2009) recommends V873 Her continue to be observed as an ideal target for stellar seismology. V2455 Cyg should also have continued photometric observations to more accurately describe its period, especially since it is a High-Amplitude δ Scuti that is drastically understudied. Observers at BYU have already obtained several more nights of photometric data on V2455 Cyg in an effort to more completely understand it.

Overall, this study was meant to be a test-run, an experiment in using a method of data reduction to see what kind of results would occur. In this capacity, this study is a success, but is only the beginning of a much larger search. A more complete treatment of the subject would include the same set of observations, both photometric and spectroscopic, for many types of δ Scuti stars. From what we have seen, the high-amplitude variables will give the best results, but both medium-amplitude and low-amplitude stars should also be observed. The biggest question that should be investigated is: what kind of information can the phase difference between the temperature curve and the luminosity curve give? If this phase difference could be shown against all kinds of quantities: spectral type, amplitude, period, overall temperature, then we might find that the difference in phase is directly related to one of these quantities. Since the phase difference between the two is due to the dependence of radius of the star on the luminosity, it seems likely that any relationship that is discovered should give us information on the radii of these stars. If we could then compare that result to radial velocities or specific gravities, we could verify the results. All this could only be done, though with a more thorough investigation of these stars, and with a much wider range of stars to look at.

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Appendix A

Header Correction Code

The following is the complete code of *opoheaders* and *wmoheaders* which are referred to in the analysis section.

```
#opoeaders --  IRAF script that should make the raw frames ready to
#be changed to FITS files by doing the
#necessary changes in the headers.  Specifically for the OPO

procedure headers ()
begin

#Local Variables-filled in later
string zimg, dimg, fimg, oimg, cmds

#Specify the filename of the zeroes
print("Enter the base filename for the zeroes:")
scanf ("%20s", zimg)

#Specify the filename of the darks
print("Enter the base filename for the darks:")
scanf ("%20s", dimg)

#Specify the filename of the flats
print("Enter the base filename for the flats:")
scanf ("%20s", fimg)
```

```
#Specify the filename of the object images
print("Enter the base filename for the object images:")
scanf ("%20s", oimg)

#Specify the filename of the CMDS files
print("Enter the base filename for the cmds files:")
scanf ("%20s", cmds)

#Edit the header of the zeroes changing imagetype to zero
print("Editing Zeroes")
hedit (zimg//"*", fields="IMAGETYP", value="zero")
hedit (zimg//"*", fields="OBJECT", value = "Zero")

#Edit the header of the darks changing the imagetype to dark
print("Editing Darks")
hedit (dimg//"*", fields="IMAGETYP", value="dark")
hedit (dimg//"*", fields="OBJECT", value = "Dark")

#Edit the header of the flats changeing imagetype and adding the subset field
print("Editing Flats")
hedit (fimg//"*", fields="IMAGETYP", value="flat")
hedit (fimg//"*i*.*", fields="SUBSET", value="I")
hedit (fimg//"*b*.*", fields="SUBSET", value="B")
hedit (fimg//"*v*.*", fields="SUBSET", value="V")
hedit (fimg//"*r*.*", fields="SUBSET", value="R")

#Perform Asthedit on the object images
print("Editing Object Images")
asthedit(oimg//"*.f*", cmds//".cmds")
```

```
#Perform SetJD on the object images
print("Setting HJD")
setjd(oimg//"*.f*")

#Perform SetAirMass on the object images
print("Setting Airmass")
setairmass(oimg//"*.f*")

beep
end

#wmoheaders --  IRAF script that should make the raw frames ready to be
#changed to FITS files by doing the
#necessary changes in the headers.  Specifically for the WMO

procedure headers ()
begin

#Local Variables-filled in later
string zimg, dimg, fimg, oimg, cmds

#Specify the filename of the zeroes
print("Enter the base filename for the zeroes:")
scanf ("%20s", zimg)

#Specify the filename of the darks
print("Enter the base filename for the darks:")
scanf ("%20s", dimg)
```

```
#Specify the filename of the flats
print("Enter the base filename for the flats:")
scanf ("%20s", fimg)

#Specify the filename of the object images
print("Enter the base filename for the object images:")
scanf ("%20s", oimg)

#Specify the filename of the CMDS files
print("Enter the base filename for the cmds files:")
scanf ("%20s", cmds)

#Edit the header of the zeroes changing imagetype to zero
print("Editing Zeroes")
hedit (zimg//"*", fields="IMAGETYP", value="zero")
hedit (zimg//"*", fields="OBJECT", value = "Zero")

#Edit the header of the darks changing the imagetype to dark
print("Editing Darks")
hedit (dimg//"*", fields="IMAGETYP", value="dark")
hedit (dimg//"*", fields="OBJECT", value = "Dark")

#Edit the header of the flats changeing imagetype and adding the subset field
print("Editing Flats")
hedit (fimg//"*", fields="IMAGETYP", value="flat")
hedit (fimg//"*i*.*", fields="SUBSET", value="I")
hedit (fimg//"*b*.*", fields="SUBSET", value="B")
hedit (fimg//"*v*.*", fields="SUBSET", value="V")
```

```
hedit (fimg//"*r*.*", fields="SUBSET", value="R")

#Perform Asthedit on the object images
print("Editing Object Images")
asthedit(oimg//"*.F*", cmds//".cmds")

#Perform SetJD on the object images
print("Setting HJD")
setjd(oimg//"*.F*")

#Perform SetAirMass on the object images
print("Setting Airmass")
setairmass(oimg//"*.F*")

beep
end
```

Appendix B

Nightphot4 Code

The following is the complete code of the $NightPhot4$ program referred to in the analysis section.

```
# NIGHTPHOT -- IRAF script designed to make photing a million files a lot
#easier without having to do each frame individually.

procedure nightphot (images, center_file)

string images {prompt="Root name of images to phot"}
string center_file {prompt="File of approximate centers (ds9.reg)"}
struct *list, *list2

begin
# Local variables
string imagelist
string img
  string imgroot
string coordfile, tmp5
int    i, end1, end2, tmp1, tmp2, tmp3, tmp4
real   temp, FWHM, temp2, temp3, intfwhm, inthwhm

# Make sure the noao and apphot or daophot packages are loaded
if (! defpac ("digiphot")) {
    print ("You have not loaded the apphot or daophot package.")
    print ("One of these packages must be loaded before continuing.")
```

```
    bye
}
# Create a text file list of images to phot.
imagelist = mktemp ("tmp$night")
imgroot = images
sections (images//"*", > imagelist)

# Open the list of images and scan through it.
list = imagelist
coordfile = center_file
        #print ("What is you starting FWHM value from IMEXAM")
#scanf ("%f", intfwhm)
while (fscan (list, img) != EOF) {

    # Display the current image frame in frame 1.  This allows the
    # frame to appear fresh without markings, etc.
    display (img, 1)

    # Call the tvmark command to allow the user to see if his/her stars
    # are correctly centered.
    tvmark (1, coords=coordfile)

            # Ask the user to input whether to continue or not.
    end1 = 0
    while (end1 == 0){
        print ("Are your stars marked and labeled correctly?
                    (0 if no, 1 if yes)")
        scanf ("%d",tmp3)
if (tmp3 != 0 && tmp3 != 1)
```

```
    print ("You entered an incorrect response!")
if (tmp3 == 0){
            while (tmp3 == 0) {
        display (img, 1)
        print ("Please re-mark the stars and save as \"ds9.reg\"")
        print ("Once you are done please enter 1 to continue.")
        scanf ("%d", tmp4)
        if (tmp4 != 1)
            print ("You entered an incorrect response!")
        if (tmp4 == 1)
            tmp3 = 1
}
}
if (tmp3 == 1){
    coordfile = "ds9.reg"
    end1 = 1
}
            }

            # PSFMeasure Command
            psfmeasure(img)
    print ("Input the FWHM values determined by PSFMeasure")
    scanf ("%f", intfwhm)
    hedit (img, fields="FWHM", value=intfwhm)
    temp = intfwhm
            temp2 = 4*real(s1)
            temp3 = 3*intfwhm

    # Get rid of the ".imh" extension
```

```
i = strlen (img)
if (substr (img, i-3, i) == ".imh")
   img = substr (img, 1, i-4)

# Call the phot command
        photpars.apertur = temp
        fitskypars.annulus = temp3
phot (img, "", coords=coordfile, output="default", verify=no,
            update=yes, verbose=yes)

# Ask the user to input whether they want to keep this ".mag.1" file.
end2 = 0
while (end2 == 0){
               print ("Are you satisfied with your results for this
                        frame (no errors)?")
       print ("Enter 1 to continue, 0 to re-phot")
       scanf ("%d", tmp1)
if (tmp1 != 0 && tmp1 != 1)
    print ("You entered an incorrect response!")
if (tmp1 == 0){
    delete img//".mag.1"
    while (tmp1 == 0){
        display (img, 1)
        print ("Please re-mark the stars and save as \"ds9.reg\"")
        print ("Once you are done please enter 1 to continue.")
        print ("This will re-phot the image frame with the new coordinates")
        scanf ("%d", tmp2)
        if (tmp2 != 1)
            print ("You entered an incorrect response!")
```

```
            if (tmp2 == 1){
        coordfile = "ds9.reg"
                phot (img, "", coords=coordfile, output="default",
                             verify=no, update=yes, verbose=yes)
        tmp1 = 1
            }
        }
                    }
    if (tmp1 == 1)
        end2 = 1
             }

     # Delete the coordinate file
     delete "ds9.reg"

     # Text dump the coordinates from the above image's mag file
     # into a new coordinate file
     txdump (img//".mag.1", "xcenter,ycenter", "yes", headers=no,
         parameters=yes, > coordfile)
}
# Create the text file for Varstar.
print ("Nightphot will now create the text file needed
            for Varstar4 or Varstar5")
print ("What would you like to name the file? (e.g. starB.lst)")
scanf ("%20s", tmp5)
txdump (imgroot//"*.mag.1", "id,mag,otime,xairmass,ifilter",
                    "yes", headers=no, parameters=yes, > tmp5)

# Clean up
```

```
delete (imagelist, ver-, >& "dev$null")
end
```