Precise Radial Velocity Curve for β-Cephei

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Abstract

A precise radial velocity curve was constructed from data taken at the Dominion Astrophysical Observatory for the star β-Cephei using a 32121 H spectrograph. The spectra, taken over a night of observing, were calibrated using a Thorium-Argon emission spectra. The chosen absorption lines for radial velocity determination were the He-I 6678 and H-α 6563 lines. First with Helium, a curve was produced with a period of 4h+35m and a maximum amplitude of 17.99 km/s. In order to mitigate centering error caused by the image slicer present in the apparatus, movement in the atmospheric Oxygen absorption lines was subtracted from the Helium data and re-plotted, yielding a period of 4h+35m and an amplitude of 18.00km/s. These values were found to be very similar to those found in literature. The same procedure was followed through with the Hydrogen-α line, confirming the magnitude of the period of pulsation, while displaying a relative phase difference. This data was found to be inadequate due to an excess of uncertainty provided by both spectral line broadening and issues with fitting a cross-correlation algorithm to the data.

I. INTRODUCTION

Construction of a precise radial velocity curve for a pulsating β-Cepheid type star is an important step along the distance ladder for interstellar objects such as galaxies. These stars follow a heuristic period-luminosity relation which proves useful in determining the relative distances from them to us[(1)]. The period comes from the rate of variability for a particular star due to a stellar mechanism known as the κ-mechanism while the luminosity of the star is dependent on the stellar type. For this paper, a β-Cepheid of type B-2 class IV star known as β-Cephei will be observed and a precise radial velocity curve will be produced. The star in question is an early population I star with very high surface temperatures reaching $\sim 20000K$. The relative changes in radial velocity due to the stars pulsation will be plotted as a function of heliocentric Julian Day in order to find a period, amplitude of variation and the phase of pulsation.

A. Theory

β-Cepheid type stars are unique in their physical characteristics even with respect to other variable stars due to their short periods of fluctuation and relatively smaller changes in radial velocity (Percy, p.117). These stars often have masses ranging from 8 to 28 solar masses and radii anywhere from 7 to 12 solar radii. In order for the internal mechanism of variability to occur, the central composition of the core of β-Cepheid have almost negligible hydrogen contents (Percy, p.119). The variations in v_{rad} are caused by a radial pulsation driven by changes in opacity of the stellar medium. These effects can be quantified by analyzing the produced spectrum of the star in question and observing changes in red- and blue-shifts of certain specific absorption lines when compared to a calibrated emission spectra.

κ-mechanism

For most standard Cepheid variables, the primary driver of periods in radial velocity is the κ-mechanism. As fusion occurs at the core of the star, the resultant radiation travels radially outwards via a random-walk process. As Helium is the second most abundant element in the star, eventually this radiation will meet a region where the photon energy is sufficient to ionize this Helium from HeII → HeIII. Before total ionization occurs, a large number of atomic energy levels are present in the helium population (LeBlanc, p.196) which increases the total amount of absorption within the Helium rapidly increasing the opacity of this stellar layer. This in turn causes a pile up of excess energy, increased internal pressure and finally a radial expansion of the entire star. This Helium-II ionization region is expanded into cooler regions of the star which allows the atoms to recombine with present free electrons driving the opacity back down again. With a lower opacity, the radiation is allowed to escape from this region, releasing the accumulated heat-energy and reducing the stellar radius once again so the cycle can begin anew (LeBlanc, p.197).

The β type of Cepheid explored in this paper has a slightly different driver of opacity variations than that of a δ-Cepheid or other variable stars. At sufficient depths of the stellar medium where temperatures exceed $\sim 200,000K$, a build up of iron metal can occur outside of the core due to atomic diffusion caused by the interplay of gravitational forces on heavier elements, like iron, and radiative forces acting on the same elements (LeBlanc, p.198). This region of iron accumulation will experience similar opacity variation as the above HeII ionization region due to the abundant absorption spectrum of iron and other heavier metallic elements(LeBlanc, p.198). The same process of periodic changes to a stellar regions opacity being the primary mover behind the radius and luminosity changes as the κ-mechanism is present for the β-Cepheid star but with a layer of heavier metals such as iron instead of pure Helium.

Radial Velocity curves

The radial pulsation of the β-Cephei star will result in shifting of the absorption spectra of the stellar medium with respect to a baseline calibrated wavelength. This is due to Doppler shifting of the line spectra for the star caused by the variations in radial velocity. Identifying These relative shifts over a period of time allows for the determination of a radial velocity curve which in turn will give the precise period of variation for the chosen star. The chosen line for this paper is the HeI 6678 Angstrom helium line. Analysis of the Hα line at 6563 Angstroms can also be done. Since most of the Helium in the star is closer to the core, the pulsation will be experienced by the Helium line earlier than that of the Hydrogen line and as such these radial velocity curves should have different phase variations.

Telluric Oxygen line correction

The telluric Oxygen lines are absorption lines caused by elemental oxygen molecules in Earth's atmosphere. They only effect ground based spectroscopy, but can contaminate the data of a star since the most prominent lines are in the optical region. For molecular oxygen, the two most important lines are the Fraunhofer A and B lines at 7600 Angstroms and 6870 Angstroms respectively[(4)]. Other Telluric lines are present in this paper's spectra such as the water absorption lines appearing near the hydrogen α line but these have no bearing on this paper. The oxygen lines in consideration can be used to calibrate the stellar spectrum since no changes in radial velocity should be apparent. The issue with using this instead of a Thorium-Argon sample however, is that changes in pressure and temperature as well as turbulence determined by the respective r_0 value will change the isotropic ratio of oxygen subsequently changing the relative position of these lines. This means that this method of calibration is only good for radial velocity changes $> 20km/s$. These telluric lines can be used to correct for errors present in an already calibrated spectra however. As an image slicer is used for this lab, there should be an amount of centering error for each line which introduces uncertainty for the center value when determining the wavelength of a shifted line. By subtracting the radial velocity shift of the atmospheric oxygen lines, systemic wavelength error can be mitigated since these O_2 lines should shift the same amount as any guiding error present in the system of measurement.

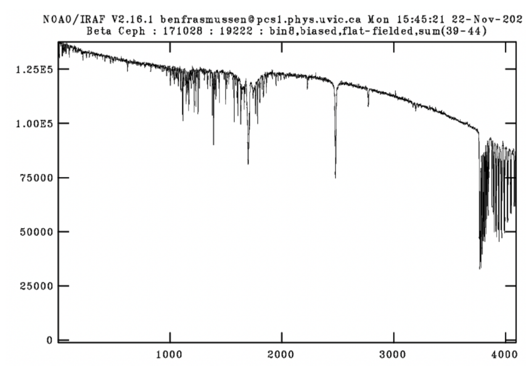

Figure 1: Stellar Spectrum of β-Cephei after corrections and before normalization

The water vapour lines present in the atmosphere can be located near the hydrogen α line near 1800 pixels while the telluric oxygen lines are noticeable after pixel value ~ 3700.

Heliocentric Julian Day

A standard Julian Day is the total count of days that have passed since GMT on the first of January of 4713 BCE[(5)]. As light has a finite speed, there is a difference between light arriving to Earth from its respective point in its orbit and that of the position of the sun. If considering relative velocities of far away objects, the roughly $\pm 60 km/s$ changes in Earth's velocity have a significant effect on these determination. The Heliocentric Julian Day takes the center of the sun as the reference point for all analysis. This represents a correction for a photon outside of the solar system to reach the center of the sun and allows for relative velocities (including pulsations in a star radius) to be standardized with respect to an orbitally corrected reference point. The Heliocentric Julian Day, or HJD, will be what is plotted as the independent variable for the radial velocity curve.

II. METHOD

To obtain the desired result, the data was recorded using the Coude focus of the 1.2 meter telescope at the Dominion Astrophysical Observatory. Alongside the large mirror, a 32121 H Spectrograph was utilized in producing the spectra of the chosen star. This spectrograph is fitted with a 32 inch collimating mirror and was incident on the DAO SITE-4 CCD with dimensions of 4096 x 2048 pixels. To finally create the required spectra, the IS 32 R image slicer was used. Various spectra of a specific β-cepheid variable star were imaged and prepped for analysis.

First, the data set was preprocessed using an iraf script in order to reduce noise and uncertainties inherent to the spectra. The steps in preprocessing included a standard average bias correction and floating-bias removal. This also included cosmic ray spike and hot pixel rejection on the bias frames. The flat-field frames, with a bias correction applied, were averaged as well, and a mean of the Thorium-Argon calibration spectra was produced. Following this, the two dimensional stellar spectra were read in and a floating-bias, dark current and bias correction were all applied to the illuminated rows. Finally, a one dimensional flat-field correction was done by treating each row in the two-dimensional spectral array as its own separate spectrum to ensure that each row was normalized accordingly. This was done so to make sure rows with insufficient signal did not dominate the final flat-field divided spectrum since smaller signal values in the flat correction would produce outlying values in the processed spectrum.

Further process of the spectra required an extraction from a two-dimensional array into a single normalizable spectrum. This was done using the built-in apsum command in iraf. By first running the script on a background corrected multidimensional spectra and then again on a preprocessed individual spectrum, the background from the first pass is smoothed before being subtracted from the final one-dimensional spectrum. In doing so, cosmic ray spikes were removed from the data using a standard variance-rejection technique. This was a problem as the command attempted to fit a line of dispersion to the data, and if this fit is inadequate in some regions, the variance-rejection used will reject parts of the data. This was avoided by increasing the baseline deviation used for the rejection, with a value of 25σ chosen for this data set.

The spectra were then normalized with respect to the continuum of the data. This was done by fitting a polynomial fit to the continuous spectra and dividing to result in unity for the continuum. The order of the fit for this particular data was chosen to be 15.

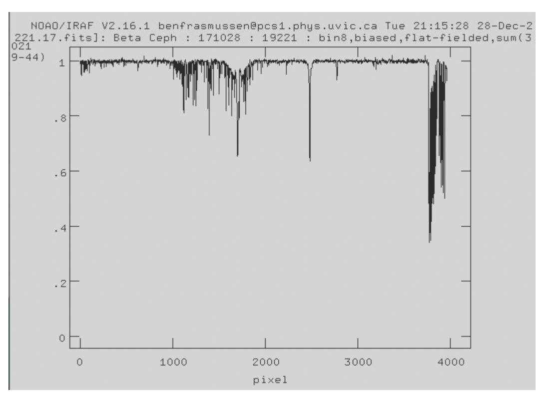

Figure 2: Example Spectrum normalized to unity using a cubic polynomial fit of order 15 for the data in the file 19221.17.fits with same noticeable features as spectrum from above.

Apart from the continuum normalization, the Thorium-Argon arc spectra underwent a similar treatment as above. Known values for each respective emission line of these spectra allowed for calibration of wavelength with respect to the pixel length of the spectra. A dispersion relation, $\lambda/pixel$, was produced by identifying each line and inputting the known corresponding wavelength of light for the centre of the line. This was done on a single Th-Ar arc file and then used as a reference for all others. A mean dispersion relation was found for the data and applied to the stellar spectra.

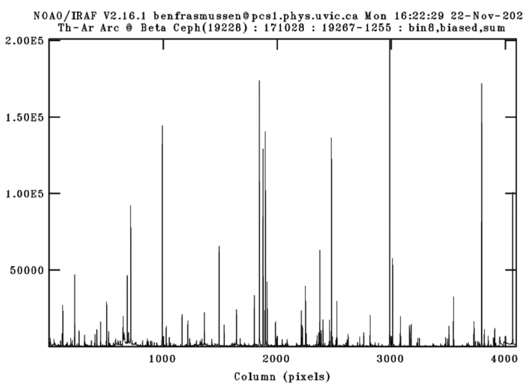

Figure 3: Thorium-Argon reference Spectra used to calibrate the β-Cephei Spectra and produce a dispersion relation for the spectrograph.

Using the refspec package, each stellar spectrum was referenced to its respective arc spectrum. This had the effect of aligning pixel values with wavelengths allowing the determination of relative positions of certain absorption lines and movement of these lines due to doppler shifting from one stellar spectra to the next. Subsequently, the dispcor command was utilized to select and interpolate certain spectral regions including the desired absorption lines were calibrated such that for each spectra, the pixel numbers all corresponded to the same wavelengths.

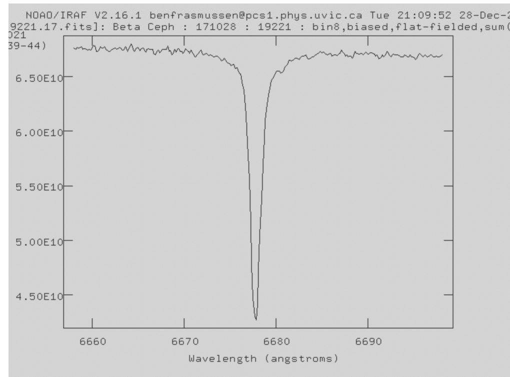

Figure 4: Example isolated Helium-I 6678 Angstrom line used for determining radial velocity for the data from 19221.17.fits.

The absorption line of interest, initially with He I 6678, were isolated and a fourier-transform cross correlation algorithm was ran on the specific line in the spectra, using a gaussian fit with width of fitting region of 7 pixels. The window of fit for the correlation plot was adjusted accordingly such that only the desired line was considered. With this fit, the heliocentric radial velocity of the star for each spectra was determined. This was then repeated for the stationary telluric oxygen lines present in the spectra to correct for any systemic wavelength errors present in the samples.

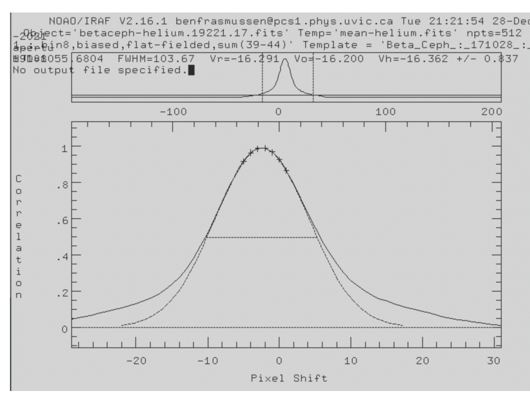

Figure 5: Example fitted Gaussian function using a Fourier-transform cross correlation algorithm to determine relative Heliocentric velocities using the Helium-I 6678 absorption line from the data 19221.17.fits.

For each sample taken, the corresponding Heliocentric Julian day was found via the header of the images. The relative radial velocity of the β-cepheid variable star was then plotted as a function of the HJD without the oxygen correction and with. An attempt to complete this procedure with the Balmer series $H\alpha$ line was completed but issues with the fxcor fit produced insufficient results.

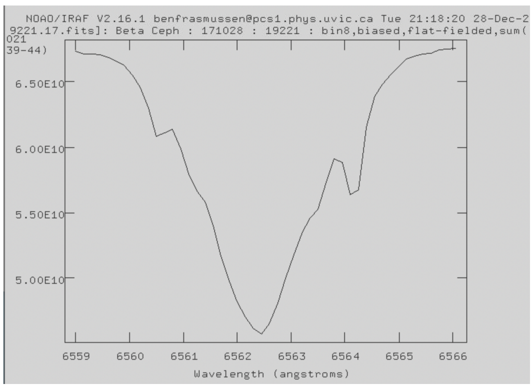

Figure 6: Example Hydrogen alpha absorption line used to produce a radial velocity curve for the data from 19221.17.fits.

III. RESULTS AND ANALYSIS

A precise radial velocity curve for the star β-Cephei was successfully created using the above method. Initially, without the telluric oxygen line correction yielded a period of pulsation of 0.190995 days or 4h+35m. The amplitude for this star resulted in a total radial velocity change of 17.99 km/s. The phase with respect to a zero was given by 0.1348 days. The residual for the sinusoidal fit for this particular curve is a value of 0.542 km/s which corresponds to the 'goodness' of the fit on this data. This information is encompassed by the following radial velocity curve for the uncorrected doppler shifting using the He-I 6678 absorption line:

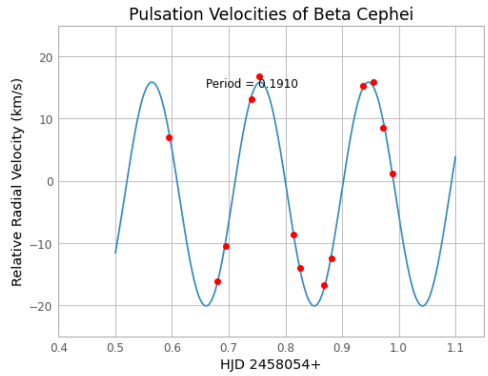

Figure 7: Uncorrected radial velocity curve for the star β-Cephei using the Helium-I 6678 absorption line.

Using the systemic correction in centering error through the use of the present telluric oxygen line corrections results in different final values for the fitted radial velocity curve. The period of pulsation was found to be 0.191085 or 4h+35m which almost matches the values found prior. The amplitude for maximum change in radial velocity due to the pulsations was given by 18.00 km/s while the relative phase was found to be 0.1342 days. The residual for this data set was 0.492 km/s which is predictably less than that of the previous uncorrected data set. This confirms that the telluric oxygen correction resulted in a better fit to the radial velocity data. The curve can be seen below:

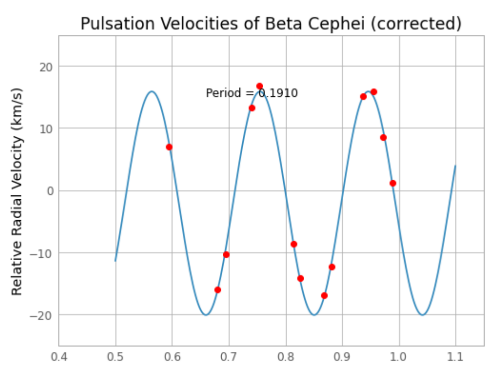

Figure 8: Oxygen line corrected radial velocity curve for the star β-Cephei using the Helium-I 6678 absorption line.

An attempt to produce the same plot for the Hydrogen-α absorption line at 6563 Angstroms was followed through using the procedure outlined in the method section. A similar period as above of 0.192904 days or 4h+37m was found in this case. A different relative phase of 0.1176 days was determined as expected. The two issues with the data set are the presence of a high residual at 1.211 km/s and a very small amplitude fitted with a zero point on the opposite side of the axis as the Helium-I line. Errors in this graph will be discussed further while the plot can be seen below:

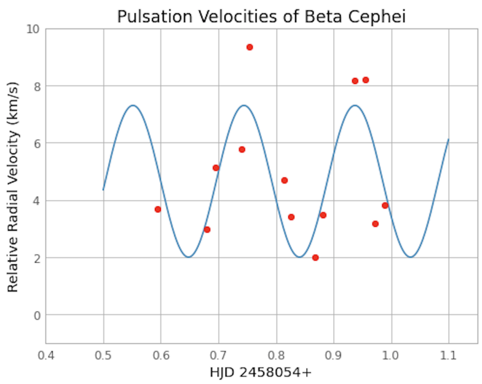

Figure 9: Hydrogen-α absorption line radial velocity curve for the star β-Cephei.

IV. DISCUSSION

Using the Helium-I absorption line, a precise radial velocity curve for the star β-Cephei was created. The period of pulsation for this particular star was found to be 4h+35m in both the uncorrected and corrected cases. The amplitude of oscillation was then found to be 17.99 and 18.00 km/s respectively. An accepted value for both these numbers is 4h+34m and 17.00 km/s (Percy, p.118). Although uncertainties were not included in the determination of these values it is safe to say that at least the period and likely the amplitude of oscillation are consistent with the literature in the Helium case.

As the residual of the sinusoid fit in the Helium case decreased after mitigating centering error via a telluric oxygen line correction, it is clear that this adjustment was successful.

A number of errors were present for both the Helium and Hydrogen case. Spectral line broadening, especially when attempting to measure subtle changes in line position in a continuum, introduces a large amount of uncertainty that was unaccounted for. This broadening was caused by a number of factors, one of which is the rotation of the star itself. A rotating star edge on to the plane of observation will cause some shifting on both sides of an otherwise sharp absorption line, contributing to experimental uncertainty. The presence of atmospheric lines in the spectra also contributed to the broadening and washing out of the lines used for observation.

More specifically in the Hydrogen case, the data was contaminated by a number of sources. Unlike the Helium-I line, H-α is surrounded by a myriad of water vapour lines from Earth's atmosphere. These lines not only contributed to line broadening, as can be seen in figure 6, but also provided some uncertainty when fitting functions to the desired line.

When comparing the two cases, the period of oscillation for the star is nearly identical which should be expected. A change in phase is also not surprising as Hydrogen should experience the pulse of the star at a slightly different time with respect to Helium that is found deeper within the star. The inconsistency is due to the offset of the zero-point of the plot as well as the maximum amplitude. The most likely explanation for this discrepancy is due to the nearby H_2O lines present. When running the Fourier-transform cross correlation on the Balmer series line, it is likely that an adjacent absorption line of water was being picked up when the spectrum was sufficiently red-shifted. This would keep large positive values for radial velocity intact while shifting any receding values up significantly which is what is seen in figure 9.

V. CONCLUSIONS

Using data taken from the 1.2m telescope at the Dominion Astrophysical Observatory and analysing spectra taken over the course of an evening, it was possible to construct a precise radial velocity curve for the star β-Cephei using the Helium-I absorption line. A correction was applied to mitigate centering error caused by the image slicer by subtracting stationary telluric oxygen line shifts and a more accurate plot of radial velocity as a function of Heliocentric Julian Day was created. The respective periods of these graphs were found to be 4h+35m for both while the amplitudes were found to be 17.99km/s and 18.00 km/s. These values largely agree with the accepted values found in the literature (Percy, p.118).

Subsequently, a plot with the Hα line was produced exhibiting similar period values as above at 4h+37m. Some discrepancies were found in this plot, likely due to spectral line broadening from stellar rotation and atmospheric oxygen lines as well as inadequate fitting to the desired Hydrogen line during the cross correlation analysis.

VI. REFERENCES

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