Improving Period Accuracy of Variable Stars

through Radial Velocity Time Corrections

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ABSTRACT

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Current variable star research makes corrections for the Earth's motion, or Heliocentric correction, to improve period accuracy. However, corrections for the star's radial motion have not been made, until now. We applied a time correction to variable star data to adjust for the radial velocity of the star and improve the period solution accuracy. From this we are investigated the appropriate number of cycles that must be observed before a reliable period can be determined. Using the time corrected data and the changes in the apparent period, for NR Lyr, V839 Cyg, and V894 Cyg, we recovered the actual radial velocity of the stars and produced the most accurate period solutions. These were, -122.224 km/s, -92.1665 km/s, -226.372 km/s, and 0.682314 days, 0.433902 days, 0.571821 days, respectively. We also used a moving source simulation to show a distinct, repeated observed-minus-calculated (O-C) pattern, and suggested a self-correcting period theory.Our results of this work suggest that radial velocity time corrections should be considered and implemented in variable star research.

Keywords: [Pulsating stars, radial velocity, time correction, O-C diagrams]

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Chapter 1

Introduction

1.1 Looking for More Accurate Period Solutions

Why do we study pulsating variable stars? These sources are often used as standard candles for sizing the Universe. Because the apparent brightness, or magnitude, of an object decreases as the square of its distance, we can find the distance to a star, or cluster of stars with the apparent and absolute brightness using the distance modulus formula. Unfortunately, absolute magnitude cannot be measured directly. However, thanks to Henrietta Leavitt, we can be find the absolute magnitude using her discovery called the Period-Luminosity Relation as shown in Figure 1.1. This relation is a direct linear relationship between the period of a given type of variable star and its luminosity, or absolute magnitude. The variable star types we discuss in this thesis are RR Lyrae type stars . These are the dim stars with periods ranging from a few hours to a few days. When we measure the period of an RR Lyrae, we can get the intrinsic luminosity from the relation. Then the distance to that star can be easily calculated, thereby helping us determine the size of the known Universe.

In the past corrections have been made to improve our period accuracy. A time correction called heliocentric correction is consistently used in variable star research. In this correction, the

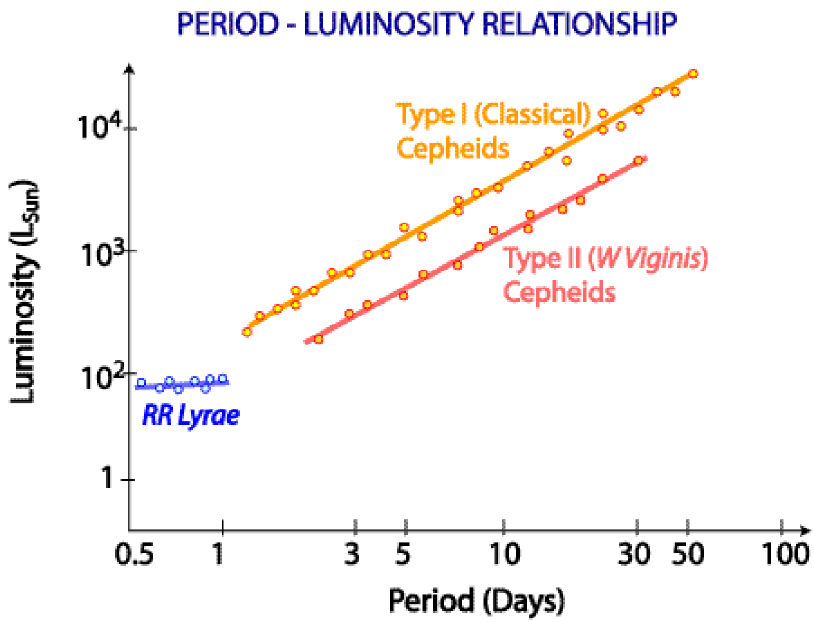

Figure 1.1 Above is the Period-Luminosity relations for the various types of variable stars. For all types there is a linear relationship between the period of pulsation and intrinsic brightness. Image from $http:$ $//www.atnf.csiro.au/outreach/education/senior/astrophysics/variable_cepheids.html$ (AustraliaTelescopeNationalFacility 2015)

observation times are corrected for the position of the Earth in its orbit, and instead we are left with the time the light would reach the Sun(Landolt & Blondeau 1972). This time is called the Heliocentric Julian Day (HJD) . With this heliocentric correction, we no longer need to worry about the movement of the Earth around the Sun, because we are essentially making our observations as if we were sitting stationary at the Sun. For variable stars this is an important correction because the velocity of the Earth creates a Doppler effect , which imposes a shift in the apparent period. Part of the year, the Earth moves toward the pulsating star, allowing for a shorter period observation, and then part of the year it moves away, causing a longer period observation (Rodler & Guggenberger 2005). This Heliocentric correction allows us to bypass correction for the Earth's velocity and we can compare observations from different times of the year.

A correction that has not yet been implemented in variable star research addresses the movement of the source relative to the Sun. We call this correction a radial velocity time correction, which will be explained further in the section 1.2. A radial velocity correction was briefly suggested by (Rodler & Guggenberger 2005) but is not commonly used like the heliocentric correction. Until recently this correction was difficult to apply: the light curve data needed, to see any change with the correction, has to be long, fairly continuous, and have times accurate to the fourth decimal place in days. Thanks to modern photometry, and projects like the Kepler Mission , we can get light curves of numerous variable stars that have these characteristics. In this thesis, we suggest it is time radial velocity time corrections be considered in variable star research.

1.2 Description of Radial Velocity Time Corrections

When a light source, like a pulsating star, is moving relative to an observer radially, the signal becomes stretched or compressed in time. This is due to the Doppler effect, shown in Figure 1.2 . As the pulsating star moves towards us, the light curve gets compressed, shortening the period. As

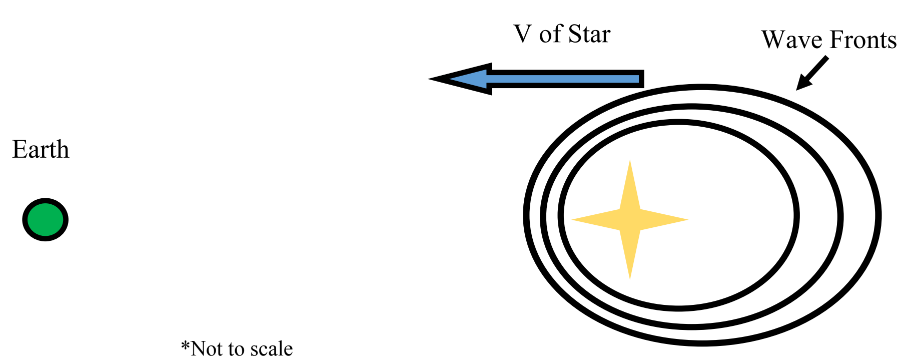

Figure 1.2 This illustrates how the radial velocity of the pulsating star can cause changes in the apparent period.

the source moves away from us, the light curve gets stretched, lengthening the period. If we know the velocity of a star relative to the Sun we can correct for the time stretching, or compressing. This is the radial velocity time correction . By making this time correction, we can improve the accuracy of the data we collect for moving sources, and therefore better understand what is going on with these distant stars and their pulsating periods.

In section 2.1, you will find details on how a radial velocity time correction is made on a variable star light curve.

1.3 What are O-C Diagrams and What Can They Tell Us

An observed-minus-calculated (O-C) diagram is a standard tool in variable star research. It is simply a graph of the observed times of maxima, or minima of a light curve, minus the calculated or predicted times. These values can then plotted against either time in HJD , or against the cycle number, which is called the epoch . The O-C values, also known as residuals, are typically plotted on the y-axis, while the epoch is along the x-axis.

To construct an O-C diagram we must find a good model that will predict when these times of maximum light will occur. This model is called an ephemeris . The ephemeris uses our knowledge about the pulsating star's period and calculates when a maximum will occur in the light curve. The most basic ephemeris is a linear relationship between period and time, and is represented by the equation

$$HJD_c = t_0 + PE, \tag{1.1}$$

where HJD_c is the calculated time of maximum light, t_0 is the first observed time of maximum, P is the estimated period from observation, and E is the epoch. After analyzing the O-C diagram the ephemeris formula can then be adjusted to better represent the variable star's periodicity.

O-C diagrams are powerful tools used to analyze subtle changes in variable star periods. If the theory represented by the ephemeris formula is accurate, the O-C diagram will be a horizontal line through zero, confirming the period accuracy. However, the other patterns in O-C diagrams gives us new and interesting information. If the diagram displays a horizontal line but at some other value besides zero this means our period is correct but the epoch is incorrect. If the O-C graph shows a straight line with a nonzero slope, the estimated period is not correct. The slope of this line is the difference between the true period and the estimated period. And lastly, the most important pattern to look for in O-C diagrams is of a star that is not perfectly periodic. This will produce a curve instead of a straight line, which indicates that the period is changing with time.

We propose in this thesis that the radial velocity of the star could result in an O-C diagram that indicates a changing apparent period over time. However if these radial velocities were included, a more accurate period could be calculated and incorporated in the ephemeris formula. Any patterns still remaining in the O-C diagram after the correction could then be accurately interpreted in terms of the properties of the star and its periodicity.

1.4 Thesis Objective

In this thesis we investigate how radial velocity time corrections improve the period accuracy of variable stars, and the patterns found in O-C diagrams. We used these radial velocity time corrections and the changes in the apparent period on three RR Lyrae variables, NR Lyr, V839 Cyg, and V894 Cyg. Following the procedure described in Chapter 2 section 2.1 and 2.2, we find a radial velocity and true time-corrected period for each. We also use a moving source simulation in section 2.3 to show a distinct, repeated O-C pattern. In Chapter 3, section 3.1 and 3.2 we analyze the improvements in the period for the three stars and draw conclusions about the patterns found in the O-C diagram. Section 3.3 outlines further work to be done.

Chapter 2

Methods for Applying the Radial Velocity Time Correction

2.1 The Process of Time Correcting and Period Analysis Improvements

The process of a radial velocity time correction is straightforward. However, due to the fact that the radial velocities of the average pulsating star are so small, on the order of 100 km/s, compared to the speed of light, the observation times must be accurate to at least four significant figures to detect any change in the time. Specifically, the time correction that takes into account the stars radial velocity is given by the equation

$$HJD_m = HJD_o - \frac{v}{c}\Delta HJD, \tag{2.1}$$

where the HJD_m is the modified or corrected time, v is the radial velocity, and c is the speed of light. As a starting point to correct with respect to, we take the first time of observation. This means the ΔHJD is the lapse in time since the first observation and the current observation at hand.

From Eq. (2.1) one finds that if the star has a negative velocity, defined as moving towards us, the corrected time is later than what was observed. Similarly, the corrected time is earlier than what was observed with a positive velocity. If our radial velocity is correct, the time correction should reverse the stretching or compressing of the light curve, thus leaving us with a light curve with the actual pulsating star period.

2.2 Use of Kepler Field Data and Period Analysis Program, Peranso

To test the idea that the radial velocity time correction would indeed improve the period solution of these stars, we used light curves of three stars, NR Lyr, V839 Cyg, and V894 Cyg. This data was obtained from the Kepler Field Data (Brown et al. 2011) because of the long data sets, over 200 days of observation, and the precise times of observation. Taking one star's light curve at a time, we analyzed the period using the period analysis program called Peranso. We found that while analyzing these light curves the periods found while looking at a data set of a short time, like five days, was different than the period found looking at a long time like 200 days. To make sure this wasn't some flaw in the program Peranso, we took increasing length data sets of a pure sine wave with a period of 1 day and found that when we graphed the dataset length versus the period it is, indeed, not a straight line indicating one period. Having a dataset of only 1 cycle can produce an error of almost 20%, and it is not until 4 or 5 cycles are observed that an error of less than 1% is reached, as illustrated in Table 2.1. However, we can stay clear of this flaw by analyzing data sets of 5 cycles or more.

We ran the procedure described in the previous paragraph, using data sets of about 10 or more cycles, for NR Lyr, V839 Cyg and V894Cyg and found there was still some variation in the apparent period with increasing data set length. These variations we define as the average distance from

Table 2.1 Comparison between sine wave dataset lengths, the period found using the period analysis program called Peranso, and the percent error from the actual, known period of 1 day. As explained in the text, an observation of 1 cycle or less yields an error of 16.9%. Furthermore, an observation of 4 cycles or more are required for an error of less than 1% using Peranso.

Dataset Length (days)	Period (days)	Percent Error
1.03450713	1.169317	16.9317
2.029225524	1.036198	3.6198
3.023943919	1.015985	1.5985
4.018662313	1.008878	0.8878
5.013380707	1.005901	0.5901
6.008099102	1.004016	0.4016
7.002817496	1.002942	0.2942
8.037324626	1.002138	0.2138
9.03204302	1.001603	0.1603
10.02676141	1.001335	0.1335
15.00035339	1.000534	0.0534
20.01373409	1.000267	0.0267
25.0271148	1.000267	0.0267
30.00070677	1.000267	0.0267
35.01408748	1	0
40.02746819	1	0
45.00106016	1	0
50.01444087	1	0

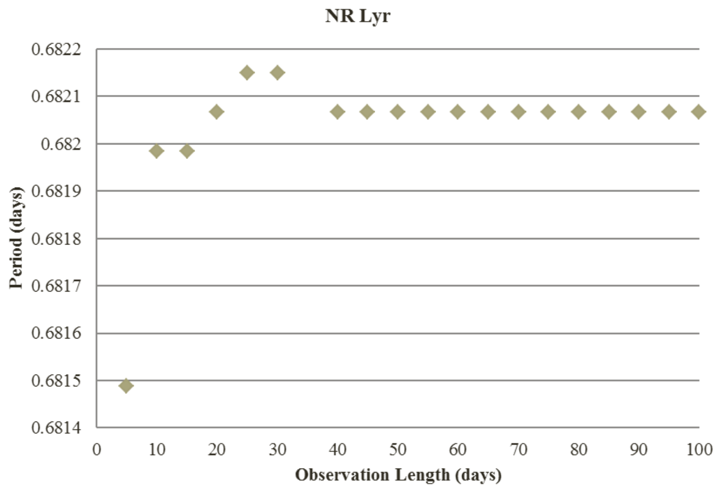

Figure 2.1 Example of period variations with increasing observation time. We can see that there are variations in the period with different dataset lengths. Eventually period solutions agree.

the natural trend line of the dataset length vs. period curve shown in Figure 2.1. Although Fig. 2.1 only shows the period variations for NR Lyr, both V839 Cyg and V894 Cyg had similar curves. We believe these variations to be a result of the radial velocity. The program Peranso could not agree at first on a period, because the radial velocity compresses the light curve. However, after many cycles, the shift in time is so small compared to the observation time, that we got a consistent period. We then produced various time-corrected datasets, correcting for velocities ranging from -50 Km/s to -300 Km/s. The theory we wished to test was that as we approach the correct radial velocity of the individual stars, the variations in the dataset length vs. period curves would decrease, producing a straight line at the most accurate period. If we were to find significant changes in these average variations as we assumed different radial velocities to correct for, we could determine a radial velocity that would indeed decrease the period variations, therefore improve the period accuracy and find that period as well.

To quantify the effect of the various radial velocity time corrections , we graphed the average variation verses radial velocity used for time correction and fit the curve. This will gave us the minimum of the curve which corresponds to the radial velocity time correction that produced the least variation in the period over time. We then took the predicted radial velocity and made the time correction to the light curve. The period of that light curve, which now takes into account the radial velocity, is the most accurate result. The results of this procedure are discussed in Chapter 3, section 3.1.

2.3 Simulation of a Moving Source and Construction of the O-C Diagram

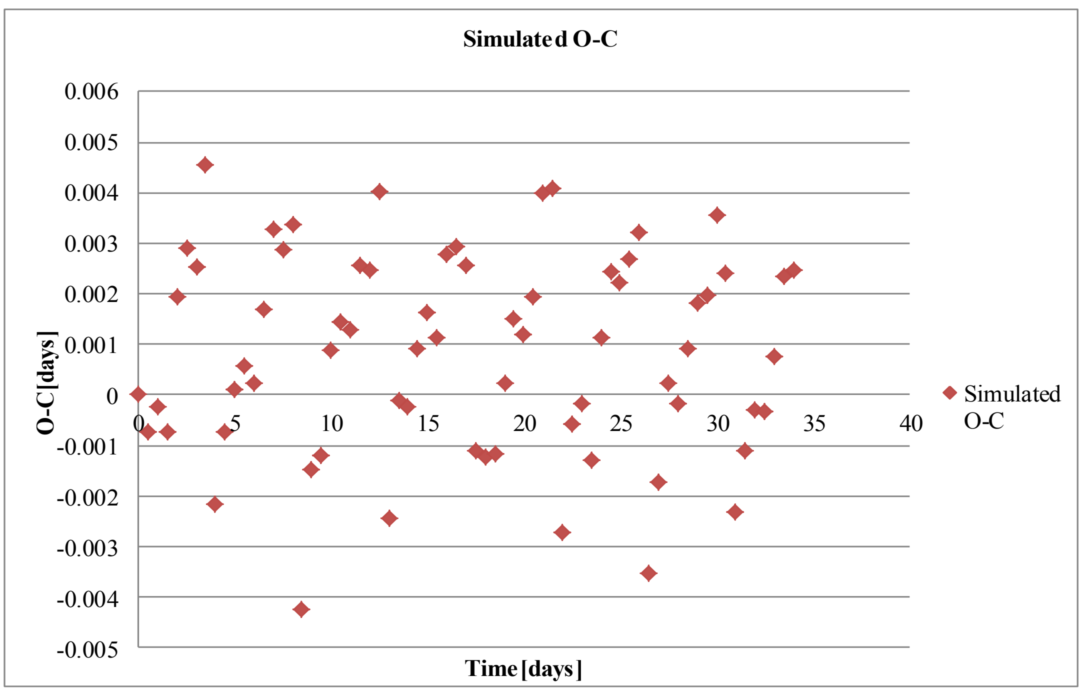

Figure 2.2 This is an O-C diagram of simulated pulsating star data, that had a radial velocity of 100 Km/s.

If the radial velocity of a pulsating star can change the period over time, then we can expect to see this in our O-C diagrams . To find out if there is some pattern found in an O-C diagram associated with radial velocity, we simulated a simple pulsating star that has a radial velocity of 100 km/s and took a look at the O-C diagram. To simulate a moving pulsating star we first generated a light curve that followed a simple sine wave. This light curve had an original period of 0.5 days. Then we used Eq. (2.1) to stretch the curve with a velocity of 100 km/s. This produced a light curve with an apparent period of 0.5001962 days. When we constructed the O-C diagram for this stretched sine wave we were surprised to see the pattern shown in Figure 2.2. We can see that the diagram has a straight line with a positive slope, indicating we have an inaccurate period in the ephemeris. What is interesting is the repetitive nature of this pattern.

We can expect, that if we made a radial velocity time corrections for the 100 km/s, which would undo the stretching we imposed on the light curve to begin with, we would have a sine wave with a known period of 0.5 days. The O-C diagram would then be a straight line at zero. This little bit of stretching changes the pattern in the diagram drastically. Conclusions on why this zig-zag-like pattern is seen when a velocity is imposed, are discussed in Chapter 3, section 3.2.

Chapter 3

Conclusions

Now that we have investigated the changes in the period variations brought on by applying radial velocity time corrections, and the patterns found in the O-C diagrams, we can discuss the results and conclusions in sections 3.1 and 3.2.

3.1 Most Accurate Period Solutions Found Using Radial Velocities

As discussed in Chapter 2, we did find the expected decrease in period variations for all three stars, which points us towards the radial velocity time correction that will yield the period with the least variations. This means, that for stars with radial velocities around 100 km/s, there is a detectable Doppler shift in the apparent light curve of the star. If we would like to know the true period of the pulsating star, the simple time correction found in Eq. (2.1) can be used on the light curve before period analysis. We will now discuss the individual period solutions and radial velocities found for NR Lyr, V839 Cyg, and V894 Cyg in the following paragraphs.

The relationship between period variation and radial velocity time correction for NR Lyr can be

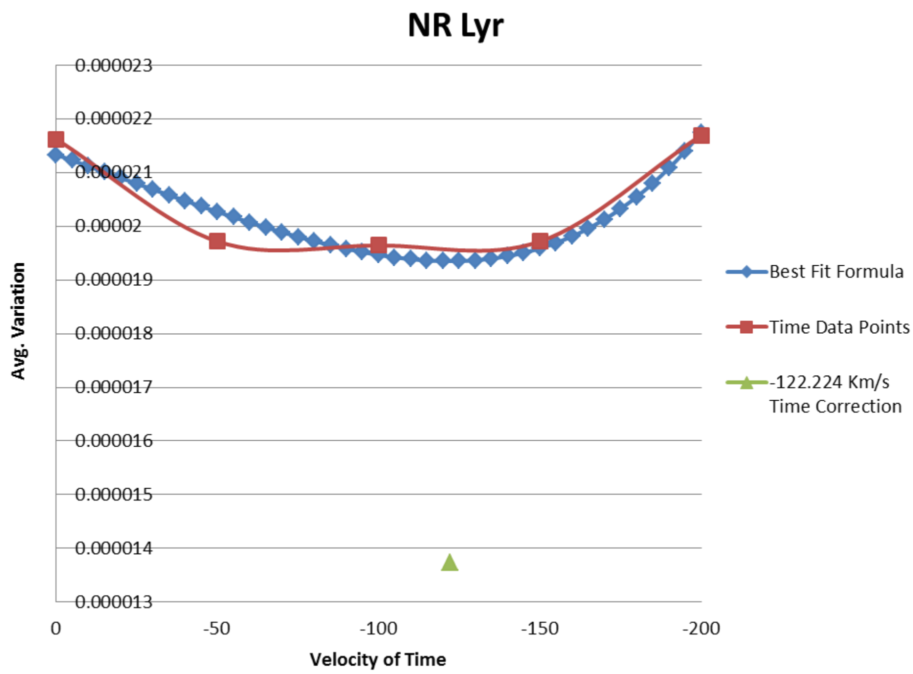

Figure 3.1 The average variation verses time correction curve. The best fit curve is also included, which is used to find a minimum variation at -122.22 km/s

seen in Fig. 3.1. We observe that the curve is similar to a parabolic function, though very shallow. Fitting the curve, we find the best fit function to be

$$y = 2.13285 \times 10^{-5} + 2.16243 \times 10^{-8} x + 2.96085 \times 10^{-15} x^4. \tag{3.1}$$

The minimum period variation of this curve clearly is not zero, but 0.000019, meaning we were not able to produce a period curve with zero variation with increasing dataset length. Nevertheless, the minimum value does point to the least period variation, and the corresponding radial velocity used in the time correction is -122.224 km/s. We conclude that for NR Lyr the radial velocity is somewhere around -122.224 km/s and when time corrected for the period produced, 0.682314 days, is the true period.

Figure 3.2 shows the relationship between period variation and radial velocity time correction

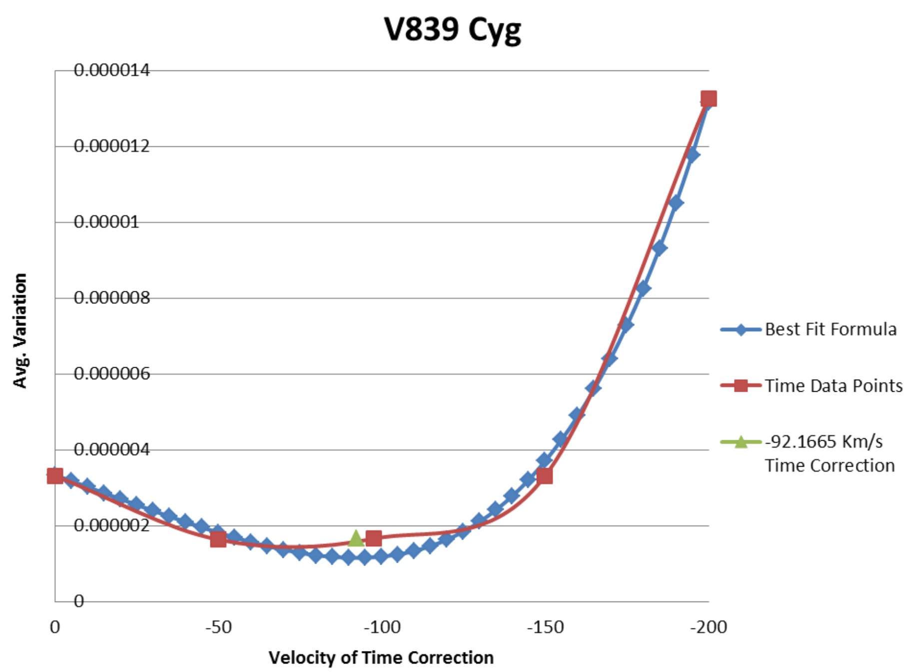

Figure 3.2 The average variation verses time correction curve for V839 Cyg. The best fit curve is also included, which is used to find a minimum variation at -92.1665 km/s

for V839 Cyg. In analogy to the NR Lyr data, the variation curve is also close to a parabolic function. The function that was found to best fit this curve was

$$y = 3.33432 \times 10^{-6} + 3.16288 \times 10^{-8} x + 1.00996 \times 10^{-14} x^4. \quad (3.2)$$

The minimum period variation of this curve, though very small, is not quite zero. However, as before, the minimum value does point to the least period variation, and the corresponding radial velocity used in the time correction is -92.1665 km/s. Therefore, V839 Cyg has a radial velocity of -92.1665 km/s and when time corrected for the period produced, which is 0.433902 days, is the true period.

Finally, we look at Fig. 3.3 for the relationship between period variation and radial velocity time correction for V894 Cyg. V894 Cyg's curve isn't quite as parabolic-like as Figures 3.1 and

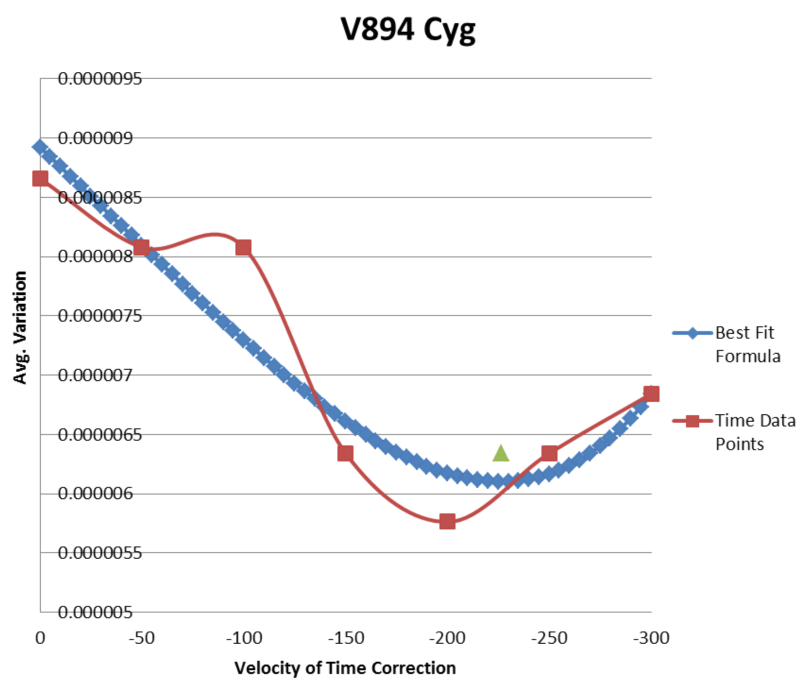

Figure 3.3 The average variation verses time correction curve for V894 Cyg. The best fit curve is also included, which is used to find a minimum variation at -226.372 km/s

3.2. This is because there appears to be no change in period variation between the -50 km/s correction and -100 km/s. However, we were still able to fit the curve, and found the best fit function to be

$$y = 8.92392 \times 10^{-6} + 1.66255 \times 10^{-8} x + 3.58299 \times 10^{-16} x^4. \quad (3.3)$$

Again the minimum period variation of the V894 Cyg curve, though very small, is not quite zero. With the minimum still being the point of least period variation, and the corresponding radial velocity used in the time correction is -226.372 km/s. Therefore, V894 Cyg has a radial velocity of -226.372 km/s and when time corrected for the period produced, which is 0.571821 days, is the true period.

We can now compare our results for all three stars to period solutions that have not had a radial velocity time correction applied (Nemec et al. 2013). Table 3.1 shows our results for NR Lyr, V839 Cyg, and V894 Cyg compared to Nemec et al. 2013. We can see that our period solutions are slightly longer, which is to be expected for stars that are approaching our solar system. Although the differences between time corrected periods and those with no time correction are small, they do increase with velocity. From Table 3.1 we can also see how similar our radial velocities are to those reported in Nemec et al. 2013. This consistency supports our use of these velocities for our time correction.

Table 3.1 Comparing our time corrected results with periods produced using no radial velocity time correction (Nemec et al. 2013). The difference is small but increases with velocity.

Variable Stars	Radial Velocity (km/s)	Nemec et al. 2013 Radial Velocity (km/s)	Corrected Period (days)	Nemec et al. 2013 Period (days)	% Difference in the Period
NR Lyr	-122.22	-124.30	0.682314	0.6820264	0.042
V839 Cyg	-92.1665	-93.78	0.433902	0.4337747	0.029
V894 Cyg	-226.372	-228.90	0.571821	0.5713866	0.076

3.2 Proposed "Self-Correcting Period" Theory

After looking at the zig-zag-like pattern in the O-C diagram of a moving source, as shown in Fig. 2.2, we concluded that moving sources have a self-correcting property. Our theory is that the stretching or compressing of the light curve, due to the radial velocity, causes our ephemeris formula to be off. However, over time, maxima will briefly align with the light curve that has no stretching or compressing. We believe this is what causes the zig-zag like pattern. Reading Fig. 2.2 from left to right we see that for a time period in the ephemeris appears to be off, and then switches to being correct as the O-C points jump down to zero. This pattern of incorrect, then correct ephemeris repeats periodically, which leads us to believe the radial velocity and period could be extracted from an O-C diagram with such a periodic pattern. We are currently working on finding a relationship between the O-C pattern, radial velocity, and period of the simulated source. In the near future we hope to extend this effort to physical data like the three stars studied in this work.

3.3 In the Future

We find that radial velocity time corrections ought to be implemented in future variable star research. With the precision of our observational and analysis tools toady, we recommend making radial velocity time corrections to improve period accuracy of pulsating stars. What is still left to investigate is how these methods hold for other type variable stars, with different radial velocities.This work also leads to the important question of whether longer period stars are affected differently than shorter period stars by radial velocity time corrections. If so, correcting for the radial velocity of variable stars could change the slope of the Period-Luminosity Relation discussed in Chapter 1, thus changing our measurements of the size of the Universe.

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