THE CONNECTION BETWEEN DELTA SCUTI STARS

AND CLOSE BINARY PARAMETERS

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Introduction

1.1 Background

Pulsating stars have intrigued astronomers since the late 1500's. The first star observed to brighten and dim periodically was o Ceti. First observed by David Fabricius in 1595, the second-magnitude star eventually faded from view only to brighten back to its original magnitude. By 1660, it was established that o Ceti dimmed and brightened according to an 11 month cycle. This periodic cycle of dimming and brightening earned o Ceti the nickname Mira (wonderful). Although the first attempts to explain the changes were erroneous, the dawn of variable star astronomy had nonetheless arrived.

Thousands of stars are now known to be variable, of which pulsation is only one mechanism. The most famous class of these stars being the Cepheid variables. Named for the first variable of this class found in 1784 by the young astronomer John Goodricke, δ Cephei, these stars change brightness on the order of days rather than months. Their brightness typically changes on the order of a magnitude or more, thus they are often among the most detectable, even in galaxies beyond our Milky Way. Other classes of pulsating variables have been discovered and categorized over the

years. The most important parameters for classifying these objects are period, change in magnitude and position on the H-R diagram.

The δ Scuti class was one of the later types of pulsating variables to be found. Most of these stars display low-amplitude changes in brightness and short periods, on the order of hours although a subclass does exist where amplitudes can reach 0.30 magnitude or larger. These stars are generally still on or close to the main-sequence, crossing the instability strip. Hence, their spectral range is between A through F types. The prototype of this class is Delta Scuti which was discovered to be variable near the turn of the 19th century. Since its discovery, hundreds of stars have been included in this category. Rodriguez et al. (2000) published a comprehensive list of 636 variables, along with periods and amplitudes. This class is also one of the fastest growing classes of variables. New CCD technology is allowing photometric detection of low-amplitude variability, and Breger estimates that between 1/2 and 1/3 of the stars at the main sequence/instability strip intersection show variability between 0.003 and 0.010 magnitude (Breger 2000). With the advent of photometric campaigns such as Kepler, this family should only continue to grow substantially over the next decades.

Another major class of variable stars is the eclipsing binary stars. An appreciable percentage of the stars in our sky are among binary stars. If the stars' orbital plane lies in the line of sight with respect to observers from Earth, the stars will pass in front of each other twice in one orbital cycle. This is the famous eclipsing phenomenon. One such eclipsing star, Algol, was first observed to change brightness in 1670. An

explanation for the variation was to wait for over a century. Again, the young John Goodricke observed the magnitude changes and in 1782 hypothesized a second body passing in front of the brighter component.

There exists a subclass of binaries of which the individual components are not resolvable. These belong to a group called close binaries. Many of the components of these systems are separated by small orders of the sum of the stellar radii, generally 20 or less (Hilditch 2001, pg 1). These short distances also lead to short periods, on the order of tens of days or less. All of the binaries in this thesis fall within these ranges of separation and period.

Binary stars are important and eclipsing binaries even more so. Using spectroscopic techniques, the ratio of the velocities and thus the mass ratio can be obtained. Because the eclipsing phenomenon can be observed photometrically and the angle of inclination is known to a much greater certainty, other parameters such as individual masses, individual radii, and the ratio of their effective temperatures can be ascertained when both spectroscopic and photometric data are combined. Other orbital and component parameters able to be determined are the eccentricity of the orbit and an approximation of the percentage of the Roche Lobe filled for each component.

1.2 Pulsating Stars in Close Eclipsing Binary Systems

The investigation of pulsating variables in close eclipsing binary systems is a relatively new area of study. The first δ Scuti-type pulsating variables in eclipsing

systems were found during the 1970's with papers published throughout the decade. AB Cas was discovered to have pulsation in 1971 (Tempesti 1971), followed by Y Cam in 1974 (Broglia & Marin 1974). RS Cha and Al Hya were the last two of that decade (McInally & Austin 1977; Jøergensen & Grønbech 1978). The list grew slowly, reaching 25 by 2006 (Soydugan et al. 2006b). Most of these systems are classified as Algol-type eclipsing systems. This led Mkrtichian to introduce the term oscillating Eclipsing Algols (the term oEA used hereafter; Mkrtichian 2004). The number of systems used in this thesis is close to 40. Objects were taken from a paper in which 20 systems were collected and analyzed (Soydugan 2006a) as well as publications reporting δ Scuti-type behavior in eclipsing Algol systems since 2006.

1.3 Effects of Binarity on Pulsation

A possible relationship between the orbital and pulsational periods was found by Soydugan et al. (2006a). For their study orbital periods and pulsation periods were gathered from the literature for each system, along with other relevant orbital parameters such as mass and stellar radius. Using this information they generated a plot of the pulsation period vs. orbital period. This plot is replicated in Figure 1. They also investigated if a correlation exists between the force of the non-pulsating component on the pulsator and the pulsation period. However, only eight systems had enough relevant data published in the literature to perform the analysis. Even with a small sample, the authors claimed sufficient evidence of a correlation.

In the course of doing undergraduate research on exoplanets, Dr. Ronald Kaitchuck and I discovered a δ Scuti star near DF Peg while performing differential



Figure 1. Pulsation period in days as a function of orbital period in days for 20 close binary systems. photometry. That discovery prompted an interest in pulsating stars, during the study of which a paper exploring orbital parameters and pulsation behavior on 4 systems was found (Tsvetkov & Petrova, 1993). In the paper the idea of a resonance between the orbital and pulsation period was mentioned. Investigating this concept further led to both the Soydugan et al. papers (2006a; 2006b; herein referred to as [1] and [2] respectively). The first of these papers put forth the possible relationships between the orbital and pulsation periods and the force/pulsation correlation mentioned above. The second introduced a catalogue of close eclipsing binary systems in which at least one component fit the δ Scuti profile in terms of spectral type and mass. From these papers this master's thesis developed. It was the purpose of this project to observe targets from the catalogue and gather data from the literature in an attempt to further establish if binarity affects the pulsational behavior.

2. Stellar Dynamics

In this section some basic astrophysical principles are presented. Section 2.1 will focus on the dynamics of binary systems. Binary geometry, potential and Roche structure will be examined. In section 2.2 stellar pulsation will be considered along with the generalities of δ Scuti stars. While most of the information contained in this section is well-known, it is given here for the context of content in chapters 3 and 4, where observations of pulsating stars are presented and relationships between binarity and pulsation are obtained, respectively.

2.1 The Dynamics of Close Binary Systems

The first task is to formally define what is meant by a close binary system. R.W. Hilditch asserts we should interchange the term *close* with *interacting* to suggest that a close binary system is one in which the two stars are close enough to have their evolution affected by the presence of the companion (Hilditch 2001; pg. 2). Typically in the literature *close* implies the separation is on the order of tens of solar radii or less. For the purposes of this study, close fits both of these definitions. Of all the systems analyzed, the one with the longest orbital period is FO Ori with 18.8 days. Using Kepler's Third Law in the form

$$P^{2} = \frac{4\pi^{2}}{G(M_{1} + M_{2})}a^{3}$$
(2.1)

where *P* is the orbital period, *G* is Newton's gravitational constant, M_1 and M_2 are the masses of the respective components of the binary, and *a* is the semi-major axis. For this study M_1 and M_2 will be denoted as M_p and M_s for primary and secondary (while the majority of pulsators included herein are considered the primary component; higher temperature and usually more massive, this is not exclusively the case). This leads to a separation for FO Ori of about 46 solar radii. This result is within tens of solar radii and hence within the assumptions of much of the literature.

To describe any system in a classical manner, three variables are needed: distance, mass, and time. It is typical in the literature of binary systems to report masses and distance in units of solar masses and solar radii, respectively. In the area of pulsating variables, periods are often reported in terms of days or in frequencies of c/d, or cycles per day. These are the units of mass, distance and time that will be utilized throughout the rest of this paper. To this end, in all calculations, the value for G used is given as 2943.7 $\frac{R^3 s_{un}}{M_{sun} day^2}$ (see appendix for the

calculation of the conversion).

2.1.1 Center of Mass and Potential



Figure 2. A Binary system with components M_1 and M_2 . The Center of Mass (CM) is at the origin. r_1 and r_2 denote the distance from each component to the CM.

Figure 2.1 shows two stars, designated as M_1 and M_2 situated distances r_1 and r_2 respectively from the center of mass (the relative sizes of M_1 and M_2 are to indicate mass; it is common for the more massive star to have the smaller radius). The center of mass is shown at the origin of the x-y plane. Using the magnitudes of r_1 and r_2 with the equation of an ellipse it can be shown that binary stars have the following property:

$$\frac{M_1}{M_2} = \frac{r_2}{r_1}$$
(2.2).

The r_1 and r_2 vectors are defined as the distance from the center of the star to the center of mass, thus the sum of the vectors provide the distance between the centers of both stars, or the semi-major axis of the system. Having defined the center of mass and the distance vectors, it is possible to now describe the gravitational potential.

Figure 2.2 shows a test mass 'm' a distance r away from the center of mass of the system. The gravitational potential energy of a particle of mass 'm' a distance s from a body of mass M is given by the well-known equation

$$U = -G\frac{Mm}{s} \tag{2.3}.$$

If a second body of mass M_2 is added, the potential energy can be found by superposition of the two bodies. Because the coordinate system in Figure 2.1 is a corotating frame of reference (objects fixed with respect to the center of mass), we also must include a centrifugal term:

$$U_c = -\frac{1}{2}m\omega^2 r^2 \tag{2.4}$$

Marking each mass with subscripts to differentiate between them and adding the centrifugal term we arrive at the total potential of the system:



Figure 3. A corotating frame of reference showing a test mass 'm'.

$$U = -G(\frac{M_1m}{s_1} + \frac{M_2m}{s_2}) - \frac{1}{2}m\omega^2 r^2$$
(2.5).

If, finally, this result is divided through by the test mass m, the effective gravitational potential, Φ , is obtained. The result is

$$\Phi = -G(\frac{M_1}{s_1} + \frac{M_2}{s_2}) - \frac{1}{2}\omega^2 r^2$$
(2.6)

This result of the effective gravitational potential will also be used in Chapter 4 to investigate if the potential in a binary system affects the period of pulsation.

When the potential is analyzed, some important points in the x-y plane can be found. If we let the test mass rest on the x-axis and differentiate the potential, we find specific points where the derivative (the force) goes to zero. These are the Lagrangian points. Of particular importance for binary stars is the L₁ point. This point lies directly between the two components and is the point at which mass will flow if and when mass transfer occurs.¹

2.1.2 Roche Structure

If the effective gravitational potential is calculated at a point in the x-y plane, the value

¹For a detailed discussion on the derivation of the effective gravitational potential, see chapter 18 of Carroll & Ostlie (2007).

belongs to a group of points of which all share that same value. The surfaces these points make are called equipotential surfaces. Likewise, in three dimensions there exists a surface that encloses a volume and the points on the surface of this volume are also equipotentials. Close to each individual star, these surfaces are nearly spherical. Moving outward, they become less spherical and more tear-drop shaped. The L₁ Lagrangian point is where the tear-drop shapes for each star meet, also called the inner Lagrangian point. The largest tear-drop shape for each star is called the Roche limit. The Roche limit is the maximum volume a star can have and retain its own constituents under its own gravitational control. This maximum volume is also referred to as the Roche lobe.

An important quantity involving the Roche lobe is called the effective radius. The effective radius is the radius a sphere would have if it occupied the same volume as the Roche lobe. Several have worked to develop approximations for this quantity; perhaps the most useful is that developed by Eggleton (1983) which is good to within 1% for all mass ratios. This approximation depends on the mass ratio q (defined as M_1/M_2 , or M_2/M_1 depending on which radius is being calculated). The formula is given as:

$$\frac{R_L}{a} = \frac{0.49q^{2/3}}{0.69q^{2/3} + \ln(1+q^{1/3})}$$
(2.7)

where $q=M_2/M_1$ is used to evaluate R_{L2} and reversed to evaluate R_{L1} . One more useful approximation involves finding the equatorial radius of the Roche lobe in the y-direction as seen from the positive z-axis looking down on the x-y plane. This approximation was developed by Plavec & Kratochvil (1964) and is given as:

$$\frac{R_L(eq)}{a} = 0.378q^{-0.2084} \tag{2.8}$$

where the q in this instance is for M_2/M_1 . With this q-value the equation gives $R_L(eq)$ for M_2 (let $q = M_1/M_2$ to obtain $R_L(eq)$ of M_1). This result will play an integral role in Chapter 4 when investigating the potential on the surface of the pulsator.

One important note should be made about the foregoing analysis; the orbits are assumed to be circular or at least at a very low eccentricity (which are assumed throughout the rest of the paper). While this assumption may not be explicitly justified, numerous estimates place the time for circularization in systems with orbital periods of less than 8 days at about 10⁶ years, which is short enough that circularization should have taken place in most of the systems. Exceptions would obviously be the longer period systems, such as FO Ori and EY Ori. Results in Chapter 4, however, will give an argument for the circularization of at least FO Ori.²

2.2 Stellar Pulsation

The variability in the light curves of pulsating stars is due to periodic departure from equilibrium. Oscillations both deep inside the star and closer to the surface can cause departure from equilibrium that will, in turn, cause the luminosity changes detected in the light curves. Pulsations can be divided into two groups. Radial pulsations maintain the spherical symmetry of the star, while non-radial pulsations in general do not maintain the symmetry.

Until recently, relatively few stars have been observed to pulsate. *Carroll and Ostlie* (2007, pg. 496) estimate that only one out of 10^5 stars show pulsation. This ratio is likely to tend to unity as better detectors are produced and more precise photometric techniques are developed. New photometric campaigns, such as Kepler, should be able to provide a better estimate of the true fraction of stars in the sky that pulsate at amplitudes currently² See Hilditch (2001) for a detailed discussion on Roche structure and circularization in close binary systems.

photometrically detectable. One more reason why this ratio should increase is we now know what types of stars are likely to pulsate and which are not.

Pulsations are driven by ionization zones. The main zones are the hydrogen partial ionization zone and the He II partial ionization zone. The He partial ionization zone is deeper in the star than the Hydrogen; however they both move toward the surface as T_{eff} increases. A general description of the pulsation mechanism follows. Stellar layers are subject to compression from perturbation. The opacity of layers within a star are governed by Kramers law, which states that the opacity, κ , is given by $\kappa \propto
ho T^{-3.5}$, where ho and T are the density and temperature of the layer. Typically, the opacity decreases upon compression (Carroll and Ostlie, pg. 496; Cox 1980, pg. 137). However, for pulsations to occur, the opacity must increase so that some of the energy is damned up (otherwise energy leakage would not cause pulsational instability). In the ionization zones, the condition for an increase in opacity upon compression is found. These layers experience a phenomenon called 'temperature freezing' (Huang & Yu 1998, pg. 486). During compression, the density increases and because the temperature is 'frozen' the opacity thus increases. This allows energy in the layer to go into ionizing the atoms in these regions. Expansion in these regions occurs when enough energy has been built up. Once the layers expand they then release the heat and as the layer cools, the atoms recombine and the layer contracts to begin a new cycle. This is known as the κ mechanism.

2.2.1 Radial Pulsation

Radial pulsation is characterized by sound waves traveling in the stellar interior. Simple models show radial pulsation periods are inversely proportional to the mean density of the star.

This is the well-known period-mean density relation. This model says that lower-density stars have longer pulsation periods, while stars with higher densities have shorter periods. Advanced models and observations also share this result. The fundamental mode of radial pulsation can be thought of as a sound wave with a node at the center and an anti-node at the surface. A simple linearized model for the fundamental period is given in *Carroll and Ostlie (2007, pg. 502)* as:

$$\Pi = \frac{2\pi}{\sqrt{\frac{4}{3}\pi G\rho_0(3\gamma - 4)}}$$
(2.9)

where Π is the period, ρ_0 is the mean density, and γ is the ratio of specific heats of the gas. Although this model was built on simplified assumptions, using the density of known Cepheid variables produces periods consistent with observations. This model is also confirmed observationally in that it predicts stars with higher densities to have shorter periods, which is in fact what is observed.

Higher mode pulsations are modeled with one or more nodes between the center of the star and the surface. As the waves travel through more nodes, the shorter the pulsation period becomes. Also, as more nodes are present, the amplitudes generally decrease. Typically, only low-order radial pulsations are detectable with current photometric techniques. In general, the majority of high amplitude and long-period variables pulsate radially; usually in either the fundamental mode or the first harmonic.

Another way to write the period-mean density relationship is to invoke the 'pulsation constant', *Q*. In this form the relationship is given as $\Pi (\rho / \rho_{SUN})^{1/2} = Q$. This says that the

pulsation constant is equal to the period of the pulsating variable multiplied by the square root of the ratio of the mean densities of the variable and the sun, respectively.

2.2.2 Nonradial Pulsation

Whereas radial pulsations conserve radial symmetry, some stars pulsate such that certain regions of the stellar surface expand while others contract. As a result the spherical symmetry is broken. Such stars are said to exhibit nonradial pulsation.

To describe nonradial pulsation, spherical harmonics are utilized. The numbers ℓ and m are used to describe the surface of a sphere. ℓ has non-negative values and m can be equal to any integer between the values of $-\ell$ and $+\ell$. ℓ represents the number of nodal circles, and there are |m| circles running through the poles, while ℓ -|m| circles run parallel to the equator. If $\ell = 0$ then m = 0 as well, and the pulsation is purely radial. For a non-rotating star not gravitationally bound to a companion, description using spherical harmonics may prove to be difficult due to the lack of an identifiable pole. However, in the case of pulsating variables in circular orbits with a companion, the axis of rotation defines the pole.

There are two main types of nonradial oscillations. The first are called p modes; p standing for pressure. Here pressure provides the restoring force for the waves traveling in the stellar interior. The second type are called g modes. Here internal gravity waves moving through the stellar interior provide the restoring force for the sound waves.

2.2.3 Properties of δ Scuti Stars

Most of the oEA's encountered in the literature are of the δ Scuti family. These pulsating variables are found at the intersection of the instability strip and the main sequence on the H-R diagram. Because almost all of them inhabit this area, they have a specific spectral

range between about F8 and A2 (Templeton 2010) although A5 is fairly hot (e.g. HD 208238 which is an A5; Turner & Kaitchuck 2008). Most δ Scuti stars pulsate nonradially, although a few pulsate in radial modes alone (Breger 2000). Because of their spectral range and position on the H-R diagram, they have higher densities than larger amplitude variables such as classic Cepheids. As a result their periods are significantly shorter. The typical range for periods is between 0.02 and 0.25 days (or about half an hour to about 6 hours) (Breger 2000). Several overviews of basic properties of δ Scuti stars are available, i.e. Templeton (2010), and Percy (2007). A detailed description of the current state of δ Scuti stars is given by Breger (2000).

Because most δ Scuti stars exhibit nonradial pulsation, and oEA are typically δ Scuti stars, we can regard the pulsations analyzed in Chapter 4 as generally nonradial in nature. It is rather curious that to date nothing in the literature indicates the discovery of larger amplitude variables such as Cepheids or RR Lyrae stars in these close binary systems. There may be a physical limitation to the development of these types of variables in close systems due to the proximity of the companion. However, if they existed, it is plausible that they would be the first discovered due to their large variability. This is not the case. The rate at which small amplitude variables (and by extension variables in places such as close binary systems) is increasing due to such programs as HIPPARCOS, MACHO, and OGLE (Breger 2000). With the dawn of the Kepler age, the rate of these discoveries should only accelerate.

3. Observations

3.1 Target List

All of the targets for this research project were taken from Soydugan et al. (2006b). The targets were chosen based on factors such as magnitude, length of time available to observe the target, and position in the sky. For this study 15 targets were chosen with possible pulsation detected in six of those targets (FO Ori was observed for a different research project but periodicity was detected once the data were analyzed). This suggests photometrically detectable pulsation may be present in these systems on the order of 30-40 %. This is in contrast to two other campaigns working from the same catalogue. Two papers published in 2009 reported successful detection of pulsation on the order of 10 % in these systems (Dvorak, 2009; Liakos, 2009). Each study observed over 20 systems. This 10% success rate may be due to observational limits. Therefore many of the targets in the catalogue already published in the literature without detection of pulsation should be looked at again by observers with different equipment than those of the author(s). X Tri was observed by Liakos et al. (2009) and pulsational variability was not found in their study. However, in taking data for this thesis, it was discovered to have pulsation. As a result, observers should continue to observe systems for which no pulsation has been detected as pulsation may simply be below the detection

capabilities of the publishing author. Multiple observing campaigns are encouraged to confirm or deny detectable pulsations.

Three other interesting cases should be noted. Observations of BG Peg had already been taken for purposes of this thesis before realizing it had already been published in the literature (Dvorak, 2009). Because no significant difference between the published period and the period found in my data could be found, no further observations were taken and the results have been excluded from this analysis. WY Leo, on the other hand, while published in the same study as BG Peg, was found to have significantly different periods. As I only gathered one night of observations on WY Leo, compared to the 27 gathered by Dvorak, caution is encouraged before any claims of pulsation period changes in the system are made. However, it may be worthwhile to gather more data on this system to determine if a period change has occurred or is still changing. FO Ori was observed on 3 nights in January, 2010, for an un-related study and subsequent analysis showed pulsational behavior. Therefore, although it is not in the catalogue, it was included in this study and as will be shown later, may be one of the more interesting data points for the purposes of this study.

All of the data taken for this thesis was done using differential photometry. Because the typical star in the δ Scuti region on the HR diagram is of spectral type F0-A5, the best filters to use to detect pulsations are the B and V filters. Some studies restrict their observations to the B filter alone. This was not done for this study as the Ball State observatory is not optimized for observations in the B filter and many stars that might be used for comparison might be brighter in the V filter. However, the R and I filters were excluded (pulsation amplitudes are filter-dependent with the B and V filters providing the highest amplitudes). Images were reduced

using the IRAF ccdred package, correcting for bias (underlying noise levels from the CCD), dark (thermal) and flat-field (pixel to pixel variations and impure optical) effects. Differential photometry was performed with the AIP4Win software package. The results of which were used to generate the light curves using Microsoft Excel. All light curves that indicated eclipse phenomena were fit with polynomials to flatten the data set before the period analysis was performed. It should be noted no attempt at pulsation mode identification has been made for the purposes of this thesis. Photometric errors were obtained in AIP4Win by performing a signal-to-noise calculation which included camera read noise, the gain of the camera, dark currents, and the sky background for the variable and comparison star(s). These errors were then added in quadrature to obtain the error for each individual differential measurement.

3.2 Summary of Observations

The observations for this project were taken between January of 2010 and December of 2010. The following sections relate the observations in detail. The telescopic equipment and CCD cameras are given first. The list of targets with all relevant observational data is also presented. Finally the results for positive possible pulsation detection are given.

3.2.1 Telescopes and Equipment

Data were collected with 4 different telescopes. The Ball State University Observatory houses two of the instruments. These include 0.4-m and 0.3-m diameter telescopes. Ball State is also part of the Southeastern Association for Research in Astronomy which operates a 0.9-m telescope at Kitt Peak National Observatory and a 0.6-m telescope at Cerro Tololo in Chile. The SARA telescopes are of the Cassegrain design, while the BSU scopes are Schmidt-Cassegrains.

The 0.4-m telescope at Ball State University is a Mead LX 200 with an SBIG ST-10 CCD

camera attached. The telescope has a focal ratio of f/6 and a plate scale of 0.58 arc sec per pixel. The 0.3-m telescope is a Celestron with an SBIG STL-6303 CCD camera. This telescope is at an f/11 ratio, giving a plate scale of 0.47 arc sec/ pixel. The 0.9-m telescope at KPNO has an Apogee U42 CCD camera with an f/7.5 ratio, giving a plate scale of 0.4 arc sec/ pixel. The telescope at CTIO is equipped with an Apogee Alta CCD camera at a focal ratio of f/13.5 giving a plate scale of 0.6 arc sec/pixel.

3.2.2 Observing Programs

Table 1 describes the observing program for each star. Included are the comparison stars chosen, UT and Julian Dates for each observation session, which telescope was used, and the number of images taken in each filter. Coordinates for each were obtained from the SIMBAD database when possible. In all other cases coordinates were obtained from The SKY 6 (Bisque Software, Inc. 2004). The Julian dates given are heliocentric-corrected dates for each night of observations.

Once generated each light curve was processed with the *PERANSO* (Vanmunster 2007) period analysis software package for periodic behavior on δ Scuti time scales using the Lomb-Scargle method (Lomb 1976; Scargle 1982). Each data set was period-searched between 0.01 and 0.3 days, which encompasses the accepted range of periods found in δ Scuti stars. A general rule was followed that if a night of observations on an object did not indicate periodicity then it was labeled as a low priority target. Ideally an object should be looked at for a minimum of four hours before discounting variability (δ Scuti stars have a maximum period of a little less than 8 hours thus at least half of a full possible period should be gathered to fully discount the presence of pulsation). However this was not always done as variables in the

	Target	<u>Comp</u>	<u>Check</u>	<u>UT</u>	<u>Julian</u>	<u>Instrument</u>	<u>B Images</u>	<u>V Images</u>
	<u>RA</u>	RA	RA		<u>2455000</u>			
<u>Target</u>	DEC	DEC	DEC					
AD Her	$18^{h} 50^{m} 00.3^{s}$	18 ^h 50 ^m 13.3 ^s	18 ^h 50 ^m 18.5 ^s	25-Jun-2010	372.7021	0.3-m		27
	+20° 43' 16.5"	+20° 45' 01.6"	+20° 45' 30"	28-Jun-2010	375.7534	0.9-m	86	86
AT Peg	22 ^h 13 ^m 23.5s	22 ^h 12 ^m 47.9s	22 ^h 12 ^m 56.4 ^s	19-Aug-2010	427.6592	0.3-m	50	50
	+08 [°] 25' 30.9"	+08° 33' 21.4"	+08° 31' 14.8"					
CZ Aqr	23 ^h 22 ^m 20.6 ^s	23 ^h 22 ^m 24.0 ^s	23 ^h 22 ^m 34.6 ^s	31-Jul-2010	408.7623	0.6-m	84	84
	-15° 56' 20.4"	-15° 59' 14.5"	-15° 55' 20.4"	8-Oct-2010	477.7341	0.6-m	89	84
				13-Oct-2010	482.5072	0.6-m	45	
EE Peg	21 ^h 40 ^m 01.9 ^s	21 ^h 40 ^m 17.3 ^s	21 ^h 39 ^m 04.3 ^s	18-Jun-2010	365.806	0.3-m		48
_	+09 [°] 11' 05.1"	+09° 00' 34.3"	+09° 03' 23.0"					
EG Cep	20 ^h 15 ^m 56.8 ^s	20 ^h 14 ^m 43.9 ^s	20 ^h 17 ^m 52.9 ^s	17-Aug-2010	425.7196	0.3-m	31	31
	+76 [°] 48' 35.7"	+76° 43' 11.2"	+76 [°] 40' 07.4"					
FY Ori	05 ^h 31 ^m 18.4 ^s	05 ^h 31 ^m 02.2 ^s	05 ^h 30 ^m 59.6 ^s	17-Nov-2010	517,7899	0.6-m	464	
2. 0	-05° 42' 13.5"	-05° 37' 27.5"	-05° 39' 14.6"	10-Dec-2010	540.7472	0.9-m	107	
50.0.1	or ^h ao ^m oo ^s			2 1 - 2010	400 507	0.0	400	400
FO Ori	05 28 09 [°]	05 28 35.4	05 28 19.7	2-Jan-2010	199.587	0.9-m	199	199
	+03 37 23	+03 38 45.0	+03 30 25.9	7-Jan-2010	204.0002	0.9-111	108	204
	h m c	h m c	h m c	10-Jan-2010	207.6431	0.9-m	129	180
HS Her	18" 50" 49.7 ^s	18" 50" 21.7°	18" 51 ["] 07.7 ^s	18-Jun-2010	365.6642	0.3-m		74
	+24° 43' 11.9"	+24" 38' 31.7"	+24° 38' 58.3"					
QY Aql	20 ^h 09 ^m 28.8 ^s	20 ^h 09 ^m 25 ^s	20 ^h 09 ^m 11 ^s	1-Jul-2010	378.7433	0.6-m	60	60
	+15° 18' 44.7"	+15° 17' 34"	+15° 21' 49"	15-Jul-2010	392.645	0.4-m		70
				9-Sep-2010	448.6848	0.4-m		96
RR Vul	20 ^h 54 ^m 47.6 ^s	20 ^h 54 ^m 37.7 ^s	20 ^h 54 ^m 48.8 ^s	6-Oct-2010	475.6726	0.4-m		60
	+27° 55' 05.7"	+27° 53' 11.2"	+27° 57' 54.2"	7-Oct-2010	476.5624	0.4-m		104
SW CMa	07 ^h 08 ^m 15.2 ^s	07 ^h 07 ^m 54.9 ^s	07 ^h 07 ^m 53.8 ^s	7-Apr-2010	293.5004	0.6-m		318
	-22° 26' 25.3"	-22° 23' 26.1"	-22° 25' 57.2"					
SY Cen	13 ^h 41 ^m 51.5 ^s	13 ^h 42 ^m 04.6 ^s	13 ^h 41 ^m 52.1"	31-May-2010	348.4475	0.6-m		162
	-61° 46' 10.1"	-61° 44' 58.1"	-61° 44' 35.2"					
UX Her	17 ^h 54 ^m 07.8 ^s	17 ^h 54 ^m 06.6 ^s	17 ^h 54 ^m 13.0 ^s	25-Jun-2010	372.6583	0.4-m		93
	+16° 56' 37.8"	+16° 58' 14.8"	+17° 04' 37.8"					
V805 Adl	19 ^h 06 ^m 18 2 ^s	19 ^h 06 ^m 16 3 ^s	19 ^h 06 ^m 12 6 ^s	18-lup-2010	365 7374	0.4-m		50
1003 Aqi	-11° 38' 57.3"	-11° 35' 39.9"	-11° 33' 18.3"	10 Juli 2010	505.7574	0.4 m		50
	$00^{h} 21^{m} 01 1^{s}$			20 Mar 2010	294 6491	0.0 m		115
VV T LEO	+16° 39' 25 2"	09 30 52.5 +16° 33' 28 0"	09 30 54.1 +16° 35' 46 1"	29-11191-2010	204.0481	0.9-m		112
V T-:	$\Omega^h \Omega \Omega^m \Omega \Omega \tau^s$	$\Omega^h \Omega^m \Omega \Omega \sigma^s$	$\Omega^h \Omega^m \Omega^\pi \Omega^s$	6 Oct 2010	475 7550	0.4 ~~		101
A 111	+27 [°] 53' 19 2"	02 00 30.0 +27 [°] 47' ∩5 9"	02 00 37.8 +27° 55' 10 8"	7-0ct-2010	475.7550	0.4-m		212
		, ., 00.0	1. 23 10.0			5.1111		

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Table 1. Given are coordinates for the targets and comparison stars, dates, instruments, and number of exposures.

observing runs (i.e. clouds or priority given to other targets that did show signs of pulsation) played a factor in which systems were focused on. The systems AD Her, AT Peg, and EG Ceph did not meet the 4 hour requirement. Nonetheless, for the data acquired on those systems *PERANSO* did not give positive results for periodic variability.

SY Cen showed periodicity. However, this is based on one night of observations. Only one usable night of telescope time at Cerro Tololo was allocated to the project while SY Cen was observable. Thus, this object, above the others, is recommended for further observations to determine if periodicity does exist. On the other hand, RR Vul's light curve indicated possible periodicity from visual inspection. However, PERANSO did not detect a dominant period to sufficient confidence levels. Again, further study on this object is encouraged in order to confirm the absence or presence of pulsation.

An object was determined to have strong periodicity if the period window in *PERANSO* showed a dominant peak above the noise in the Lomb-Scargle statistic (theta) and if this peak was not associated with a peak in the spectral window (the peaks in the spectral window show how the data were sampled). Only peaks in the period window that were not found to be artifacts of the observing schedule were deemed as a peak possibly due to stellar pulsation. The pre-whitening function was also used to remove the dominant peak in order to look for evidence of multi-periodicity.

3.3.1 Results

The results of positive detection for periodic behavior are presented in this section. Of the observed systems, six were found to have strong periodicity and have not been published in the literature. WY Leo was found to have periodicity but different from that already published

<u>Target</u>	Porb	P Pulse	<u>Amplitude</u>
	<u>(day)</u>	<u>(day)</u>	<u>(mmag)</u>
AD Her	9.7666		
AT Peg	1.1461		
CZ Aqr	0.8628	0.0331(2)	12
EE Peg	2.6282		
EG Cep	0.5446		
EY Ori	16.7878	0.1030(20)	20
FO Ori	18.8006	0.0292(2)	5
HS Her	1.6374		
QY Aql	7.2296	0.1119(24)	12
RR Vul	5.0507		
SW CMa	10.092		
SY Cen	6.6314	0.0936(119)	12
UX Her	1.5489		
V805 Aql	2.4082		
WY Leo	4.9859	0.0457(28)*	?????
X Tri	0.9715	0.022(1)	10

Table 2. Given are the orbital and pulsation periods, and the amplitudes. The asterisk by the pulsation period of WY Leo denotes that the pulsation period differs from that found by Dvorak (2009), while the question marks in the amplitude column indicate the amplitude was not constant throughout the data set (see Fig. 24).

(see above comments). Table 2 gives the orbital period of each system observed, the dominant pulsation period (if detected), and the measured amplitude. All amplitudes were measured with the half-amplitude method. The numbers in parentheses represent the uncertainty on the measurements as determined by *PERANSO*. Each system will be discussed in detail with sample light curves and power-spectra given.

In each case a description of the results of each system in which pulsation was detected is given with all associated figures relegated to the end of this chapter (error bars are included on all light curves).

CZ Aqr

CZ Aqr was observed on three nights, 31-July, 8-Oct, and 13-Oct-2010 (UT). A total of 218 images in the B-filter and 164 in the V-filter were acquired. The light curve in the B- filter for 31-July-2010 (UT) is shown below in Figure 4. The photometric errors for the night ranged between 1.8 and 2 millimag. The results of the period search are shown in Figure 5. The determined period is 0.0331 ± 0.0002 days. Figure 6 shows the power spectrum after the removal of the 0.0331 day peak. It is possible these residual peaks are indicative of CZ Aqr having multiple modes of pulsation. However, further observations will be needed to confirm whether or not CZ Aqr is indeed multi-modal at current photometric levels. Figure 7 shows the data for the 3 nights in the B-filter phased onto the 0.0331-day period.



Figure 4. Light curve for CZ Aqr on the night of 31-July-2010 (UT).



Figure 5. Power-spectrum for CZ Aqr with peak at 0.0331 day.



Figure 6. Power-spectrum of CZ Aqr with the 0.0331 day peak removed. Residual is 0.0325 day.



Figure 7. Data for CZ Aqr phased onto the single 0.0331 day period.

EY Ori

Observations on EY Ori were performed on 17-Nov-2010 and 10-Dec-2010 (UT). A total of 571 images were acquired in the B-Filter over the course of the two nights. The light curve for the night of 17-Nov-2010 is shown in Figure 8. The amplitude is on the order of 20 millimag while the photometric errors ranged between 3.0 and 4.0 millimag. The period was determined to be 0.1030 ± 0.0020 day. Figure 9 shows the power-spectrum with the 0.1030 day period, while Figure 10 shows the power-spectrum with the 0.1030-day period removed. The residual shows a peak at 0.0621 ± 0.0007 day and the data folded onto a single phase for both the dominant and secondary periods are shown in figures 11 and 12, respectively. The phase diagram for the secondary period is suggestive of multi-modal behavior.



Figure 8. Light curve of EY Ori on night of 17-Nov-2010 (UT).



Figure 9. Power-spectrum for EY Ori with peak at 0.1030 day.



Figure 10. Power-spectrum of EY Ori after removal of 0.1030 day period. Residual is 0.0621 day.



Figure 11. Data for EY Ori folded onto the 0.1030 day period.





FO Ori

Data on FO Ori were acquired over the course of three days in January, 2010 with the 0.9-m telescope. FO Ori was originally observed as part of a separate project at Ball State University by faculty member Dr. Ronald Kaitchuck and students, Joe Childers, Ken Moorehead, Danielle Dabler, Matthew Knote, Elizabeth Beal and me. However, after periodicity at low photometric levels was discovered, it was added to the study of this thesis. It was deemed a potentially important data point as the original Pulsation Period vs. Orbital Period relationship

given by Soydugan et al. did not have orbital periods beyond 10 days. FO Ori's 18.8 day orbital period thus serves as an interesting check case for the validity of any such relationship beyond periods of 10 days. The implications for the validity of a Period/Period relationship will be given in Chapter 4.

Analysis of the 496 images in the B filter revealed a dominant period of 0.0292 ± 0.0002 day and a secondary period of 0.0297 ± 0.0002 day (the 583 images in the V filter give 0.0289 ± 0.0002 day for the dominant period, thus in good agreement; although more images were taken in the V filter, the B filter data was slightly cleaner consistently). The light curve for the night of 3-January-2010 in the B-filter is shown in figure 13. Figure 14 shows the power-spectra in the B filter for the three nights giving the dominant 0.0292 day. Figure 15 shows the 0.0297 day period with the 0.0292 day period removed. Thus, again multi-periodicity is implied. Data folded onto single phases of each period can be seen in Figures 16 and 17, respectively. The amplitude of pulsation is about 50 millimag while the photometric errors were consistently (within ten percent) one millimag.



Figure 13. Light Curve for FO Ori on 3-Jan-2010 (UT).



Figure 14. Power-spectrum of FO Ori in the B filter showing peak at 0.0292 days.


Figure 15. Power-spectrum of FO Ori in the B filter with 0.0297 day peak after 0.0292 day peak removed



Figure 16. FO Ori B filter data phased onto the 0.0292 day period.



Figure 17. FO Ori B filter data phased onto the 0.0297 day period after 0.0292 day period removed.

QY Aql

QY Aql was observed on three separate nights using the 0.4-m telescope at Ball State. Analysis of the data acquired on the nights of 1-July-2010, 15-July-2010, and 9-Sep-2010 show a period of 0.1119 ± 0.0024 day. A secondary period of 0.1030 ± 0.0020 day is found after removing the dominant period however the difference between the two frequencies is close to 1 c/d, implying this may be an artifact of 24-hour aliasing. Nonetheless, removal of this period from the period search reveals a secondary period at 0.1196 ± 0.0028 days. Figure 18 show the light curve in the V-Filter on the night of 1-July-2010 showing amplitude of about 10 millimag. The photometric errors associated with that night were two millimag or less. Power-spectra for the 0.1119 and 0.1196 day periods are shown in figures 19 and 20. The data folded onto the 0.1119 day period is shown in figure 21.



Figure 18. Light Curve for QY Aql in the V filter on the night of 1-July-2010 (UT).







Figure 20. Power-spectrum of QY Aql with peak at 0.1196 day after removal of 0.1119 day peak.



Figure 21. QY Aql V filter data phased onto the 0.1119 day period.

SY Cen

Of all the observed systems with periodicity detected, SY Cen is the most uncertain as to whether pulsation is truly present or not. Only one night of data has been acquired to date, and thus the periodicity has not been confirmed in multiple image sets, and the uncertainty in the measurement is quite large due to having only gathered one complete cycle. It is also the only target on the list for which a positive result for pulsation was detected and less than 200 images were acquired. It is strongly encouraged that further observations are obtained to confirm whether or not pulsations are indeed present or not.

Nonetheless, *PERANSO* detected periodicity from the analysis of the 162 V-filter images acquired on 31-May-2010 by the 0.6-m telescope. The light curve indicates amplitude of about 5 millimag. Photometric errors were less than 3 millimag throughout the night. The period was determined to be 0.0936 ± 0.0119 day. Figures 22 and 23 show the light curve and powerspectrum, respectively. No secondary peaks are found when removing the 0.0936 day period from the period search. This should not be surprising as observations were only taken one night. Also as a consequence, no 24 hour aliases are found in the power-spectra.



Figure 22. SY Cen on the night of 31-May-2010 (UT) in the V filter.



Figure 23. Power-spectrum of SY Cen in the V filter on the night of 31-May-2010.

WY Leo

As mentioned above, WY Leo has already been published in the literature (Dvorak, 2009) with a reported period of 0.0656 day. The author reported observations totaling 27 nights. The amplitude was determined to be 11 ± 1 millimag. The observations for the earlier study were taken on a 0.25-m Meade Schmidt-Cassegrain with an SBIG ST-9XE CCD in the B and V filters.

These observations are in contrast to those performed for the purposes of this thesis. As indicated in Table 1, observations on WY Leo were performed on the night of 29-March-2010. A total of 115 images were obtained on the 0.9 meter telescope in the V filter. The light curve showed definite variability, however the level of variability changed throughout the data set and thus definitive amplitude could not be determined. Photometric errors ranged between 1.5 and 1.8 millimag. The light curve is shown in Figure 24. The determined period for the observations obtained that night was 0.0457 ±0.0028 day (the power-spectrum is shown in Figure 25). The asterisk in Table 2 next to the value of pulsation period indicates this differs from that obtained by Dvorak. Thus it is possible some mechanism has been affecting the system causing a period change. If this is the case, it would be a very significant period change in a short amount of time and would be worth further study. On the other hand, it is cautioned that for this thesis only one night of observations have been gathered, compared to the 27 nights by Dvorak. It is possible the period has not changed from the 0.0656 day obtained earlier, but not enough cycles were obtained in one night of observing to detect the dominant period. Thus, while further study of the object is encouraged, the caveat that one night of datataking should not be regarded as proof of change in the periodicity of the system. Data were

taken on the night of 15-Jan2010 also from the 0.9-m telescope. However the quality of the data was not good enough to be included in this study. Because of the insufficient amount of data to show a change in periodicity, for the purposes of further analysis, the pulsation period of 0.0656 day obtained by Dvorak will be adopted.



Figure 24. Light curve for WY Leo on night of 29-March-2010 (UT) in the V filter.



Figure 25. Power-spectrum for WY Leo in the V filter showing the 0.0457 day period. The residual peak is at 0.0831 day.

X Tri

Also as stated above, X Tri has also been previously observed. However detection of pulsation in the earlier study was negative (Liakos, 2009). In their study, a 0.4-m Cassegrain telescope was used with an ST-8XMEI CCD camera. X Tri was observed on 13 separate nights in the B, V, and R filters. The observations covered a time span of 25.3 hours.

X Tri was observed for this thesis on the nights of 6-Oct-2010 and 7-Oct-2010 using the 0.4-m telescope on campus. Over the two nights, 313 images in the V filter were obtained. These observations resulted in the lowest photometric errors obtained in this study, each measurement on 6-Oct-2010 being less than one millimag and 7-Oct-2010 were 1.3 millimag or less. The light curve for 6-Oct-2010 is shown in Figure 26 (the data points do have error bars attached). The determined period of pulsation is 0.0220 ± 0.0001 day with amplitude of about 10 millimag. The power-spectrum is shown in Figure 27. Removal of the 0.0220 day period did not reveal any significant residuals in the power spectrum. It is not believed that X Tri is multiperiodic, at least in the δ Scuti regime of periods. Figure 28 shows the data folded onto the 0.0220 day period.



Figure 26. Light curve of X Tri in the V filter for the night of 6-Oct-2010 (UT).



Figure 27. Power-spectrum of X Tri in the V filter showing a peak at 0.0220 day.



Figure 28. Data for X Tri folded onto a single phase for the 0.0220 day period.

4. δ Scuti Stars in Close Binary Systems

4.1 A Literature Review

Several campaigns have been implemented searching for δ Scuti stars in close binary systems. In addition to the systems found by Kim et al. (2002), Mkrtichian et al. (2002) and others (the results of which were used for the initial relation between the orbital and pulsation periods by [1]), other campaigns have taken up the search in systems given in the catalogue by [2]. The results of these campaigns are presently collected from the literature and put together with the results of the above observing campaign. The relationship between orbital period and pulsation period was extended to include these new systems. Other relationships are also investigated including the force on the surface of the pulsating component by the secondary, resonance, and the Roche structure of the system.

Table 3 presents the values for orbital periods, masses, temperatures, and pulsation periods, as gathered from the literature. As the literature contains studies not restricted to δ Scuti variables, only systems in which δ Scuti-type pulsations are firmly established have been included in the study. From these data the pulsation period vs. orbital period relationship is extended from 20 systems to 40, while the possible relationship between the pulsation period vs. force has increased from eight systems to almost 35, six of which were added from my own observations. The data for masses, radii, and temperatures all come from [2] unless otherwise indicated. RL1 and RL2 indicate the percentage of the Roche Lobe filled for the primary and secondary components respectively. These data came from Brancewicz and Dworak (1980). Finally, the references column indicates which reference was used to find the information about the pulsation period and amplitudes. As will be noted for the study by Pigulski and Michalska (2007), only three of the systems (the classical Algols) of the reported nine systems in which δ Scuti-type pulsation were included. The authors admit in the remaining six systems the pulsation could be due to field stars as the data were taken from the third part of the All-Sky Automated Survey which had low spatial resolution. WX Eri, which was included in the list in [2] was also omitted from this study after further observations could not confirm δ Scuti-type variability but instead found γ Doradus-type variability (Arentoft et al., 2004). An interesting check for research involving δ Scuti-type variables would be to investigate if binarity seems to affect γ Doradus stars as it seems to for δ Scuti stars.

While most of the systems in Table 2 have come from [1] which introduced the relationship between the periods or [2] which introduced the catalogue from which the targets in Chapter 3 were chosen, some of the systems have been found elsewhere. As is the case for some of the systems in [1], not all of the systems have data for parameters (masses, radii, temperatures) available; hence in the following there is a discrepancy between the period analysis (40 systems) and the force analysis (35 systems). Also, while most systems are classic Algols, this study is not restricted to Algols only. Another issue is that of mass transfer. The authors of [1] mainly dealt with systems that either are currently mass-transferring or had in the past, leading to possible different evolutions than those in which transfer had not occurred.

Object	Porb	M _P	Ms	R _P	Rs	T _P	Ts	P _{pulse}	mag _{Pulse}	Roche _P	Roches	q	Ref
	day	M _{sun}	M _{sun}	R _{sun}	R _{sun}	к	К	day	mag				
RZ Cas	1.1953	2.28	0.77	1.62	1.99	8600	4480	0.0156	0.0130	51	97	0.34	1
AS Eri	2.6641	1.92	0.21	1.57	2.19	8476	5110	0.0169	0.0068	28	95	0.11	1
CT Her	1.7864	1.98	1.90	1.97	1.99	9160	7600	0.0192	0.0300	50	53	0.96	1
TZ Dra	0.8660	2.12	1.28	2.03	1.72	7900	5560	0.0194		83	89	0.60	1
VV Uma	0.6874	2.26	0.68	1.67	1.31	9106	5579	0.0195	0.0150	74	101	0.30	1
IU Per	0.8570	2.42	2.03	1.88	1.74	8150	8060	0.0238	0.0200	76	77	0.84	1
V469 Cyg	1.3125							0.0278	0.0200				1
HIP 7666	2.3723							0.0409	0.0200				1
AO Ser	0.8793	2.56	1.14	1.80	1.79	8970	6090	0.0465	0.0200	67	96	0.45	1
R CMa	1.1359	1.07	0.17	1.50	1.15	7310	4355	0.0471	0.0088	56	103	0.16	1
V346 Cyg	2.7433	2.34	1.83	3.75	4.74	8390	6640	0.0502	0.0300	70	100	0.78	1
RX Hya	2.2817	1.68	0.40	1.70	2.4	7616	4484	0.0516	0.0140	36	99	0.24	1
TZ Eri	2.6062	1.97	0.37	1.69	2.6	7770	4570	0.0534		34	52	0.19	1
TW Dra	2.8069	1.58	0.74	2.40	3.4	8355	4320	0.0556	0.0042	47	103	0.47	1
TU Her	2.2669	1.43	0.57	1.60	2.7	6300	3600	0.0556	0.0080	35	95	0.40	1
AB Cas	1.3669	2.30	1.10	1.97	1.48	8588	3900	0.0583	0.0392	41	67	0.48	1
Y Cam	3.3057	1.70	0.40	2.92	2.95	7219	4507	0.0665	0.0116	46	88	0.24	1
EF Her	4.7292	1.93	1.41	2.36	2.34	7040	6650	0.1042	0.0600	33	37	0.73	1
Al Hya	8.2897	1.98	2.15	2.77	3.92	7096	6699	0.1380	0.0200	28	24	1.09	1
AB Per	7.1603	2.08	0.52	2.52	3.73			0.1958	0.0400	23	99	0.25	1
IV Cas	0.9985	2.60	1.24	2.00	2.22	8885	6372	0.0265	0.0100	68	106	0.48	2
HD 172189	5.7020							0.0510					2
V577 Oph	6.0791	2.08	0.52	2.52	5.73	8720	5690	0.0695	0.0289	23	99	0.25	2
RS Cha	1.6699	1.89	1.87	2.15	2.36	7638	7228	0.0860	0.0168	64	60	0.99	2
RR Lep	0.9154	2.9	1.769	2.89	2.13	8970	7240	0.0314		103	95	0.61	3
BG Peg	1.9523	2.53	1.2903	2.4	3.35	8950	6900	0.0400		53	102	0.51	3
AC Tau	2.0434	1.45	0.986	2.3	2.9	7200	5920	0.0570		61	92	0.68	3
WY Leo	4.9879	2.31	1.4091	2.36	2.65	9640	7940	0.0656		40	41	0.61	3
ТҮ Сар	1.4235	2.50	2.05	2.89	2.57	7880	3780	0.0413		82	80	0.82	4
WY Cet	1.9397	2.47	1.8772	2.16	2.16	9190	8690	0.0758		50	57	0.76	4
IZ Tel	4.8802							0.0738	0.0459				5
MX Pav	5.7308							0.0756	0.0769				5
VY Mic	4.4364	2.39	1.96	2.24	4.46	8770	5320	0.0817	0.0194	30	66	0.82	5
Y Leo	1.6861	2.6						0.0290					6
X Tri	0.9715	2.3	1.2	1.71	1.96	8600	5200	0.0220	0.0100	65	92	0.52	7
FO Ori	18.8006	2.19	1.49	1.87	1.1	8900	6840	0.0286	0.0500	10	7	0.68	7
CZ Aqr	0.8628	2.96	1.48	1.91	2	7780	5860	0.0331	0.0120	69	100	0.50	7
SY Cen	6.6314	3.33	1.665	2.39	6.34	7690	4540	0.0936	0.0120	21	78	0.50	7
QY Aql	7.2296	2.69	0.7532	4.41	5.52	6930	5240	0.0972	0.0120	38	83	0.28	7
EY Ori	16.7878	2.52	2.09	3.51	8.47	7179	4816	0.1050	0.0200	19	51	0.83	7

Table 3. General Properties of close binary systems with pulsating components. References for pulsation period: (1) Soydugan et al. (2006a); (2) Soydugan et al. (2006b); (3) Dvorak (2009); (4) Liakos a& Niarchos (Liakos 2009); (5) Pigulski & Michalska (2007); (6) Turcu & Moldovan (2008); (7) Turner & Kaitchuck in the present study

Target	Orbital Period	Pulsation Period	Uncertainty		
	(days)	(days)	(days)		
CT Her	1.7864	0.018891414	4.E-09		
AS Eri	2.6641	0.01694021	1.E-08		
RZ Cas	1.1953	0.01557790	5.E-08		
AB Cas	1.3669	0.0582873	3.E-07		
Y Cam	3.3057	0.0664587	4.E-07		
VV Uma	0.6874	0.019516	3.E-06		
IU Per	0.857	0.023751	5.E-06		
Al Hya	8.2897	0.138031	6.E-06		
HIP 7666	2.3723	0.04088	1.E-05		
TW Dra	2.8069	0.05559	6.E-05		
AB Per	7.1603	0.1958	3.E-04		
TU Her	2.2669	0.0556	6.E-04		
R CMa	1.1359	0.048	2.E-03		
IV Cas	0.9958	0.03058819	7.E-08		
HD 172189	5.702	0.0510272	2.E-07		
V577 Oph	6.0791	0.069491	4.E-06		
BG Peg	1.9524	0.0400229	2.E-07		
RR Lep	0.91543	0.0313820	3.E-07		
WY Leo	4.9859	0.0655617	4.E-07		
AC Tau	2.0434	0.057035	3.E-06		
MX Pav	5.730835	0.07560166	6.E-08		
IZ Tel	4.880219	0.0737572	1.E-07		
VY Mic	4.436373	0.0817387	2.E-07		
Y Leo	1.6861	0.0289995	5.E-07		
X Tri	0.9715	0.022	1.E-04		
CZ Aqr	0.862759	0.0331	2.E-04		
QY Aql	7.2296	0.097	9.E-03		
SY Cen	6.63136	0.09	1.E-02		
EY Ori	16.7878	0.105	9.E-03		
FO Ori	18.8006	0.0286	1.E-04		

Table 4. Pulsating Systems with uncertainty in the pulsation period.

Kaitchuck et al. (1985) observed several binary systems in an effort to detect emission lines indicative of mass transfer. Of the systems shown in Table 2, six systems were analyzed by Kaitchuck et al (RZ Cas, AB Cas, TW Dra, TZ Eri, Y Leo, and X Tri). Only TZ Eri showed evidence for line emission. Although we assume all the systems have at one time transferred mass, it is arguable that such evolutionary history does not, at least to a first approximation, have much effect on the pulsation period.

From the data in Table 2, 30 systems have uncertainties listed for the pulsation periods. The remaining 10 systems did not have uncertainties reported by the authors. The conclusions drawn from analysis are therefore reduced. The systems with associated errors are listed in Table 3.

The next section compares the δ Scuti stars in Table 2 with companionless δ Stars. Afterward the effects of various orbital parameters on pulsation such as orbital period, potential, percentage of the Roche Lobe filled, and force from the companion, are investigated. Each of these will be developed with only those systems with reported uncertainties. This chapter will end with each of these relationships extended to the systems in which errors were not reported, as the relationships found in the literature typically are not fit with errors on the individual pulsation periods. This will serve as a comparison to the relationships found in the literature.

Each observed relation is given as a linear fit. This was done because no a priori theoretical reasons could be found that they should not be linear. The linear models which were fit involving errors were done using the method given in *Bevington* (2003, pg. 114), while those fit without errors were done with the basic least-squares method as can be found in *Taylor* (1982, chapters 2 and 8).

4.2 δ Scuti stars with and without companions

The first step in examining if binarity has any effect on pulsation is to look at the pulsation periods of δ Scuti stars that are not part of close binary systems and compare them



Figure 29. Histogram of δ Scuti stars in close binary systems binned by period in intervals of 0.01 days.



Figure 30. Histogram of single δ Scuti stars binned by period in intervals of 0.01 days.

with the periods of the systems in Table 2. Histograms of the systems in Table 2 and those of the catalogue of Rodriguez et al. (2000) (see Introduction) are presented in Figures 29 and 30, respectively. Although the catalogue by Rodriguez contains 636 variables, only 627 were used as nine are also in Table 2. Figures 29 and 30 were created by sorting the data by period. The data were then binned in intervals of 0.01 days, starting at 0.015 days.

Inspection of the histograms reveals significant differences. Of the 40 systems in Table 2, 38 are found to have periods of 0.105 days or less (on the order of 90 %). This is in contrast to the data from Figure 30; about 50% of single δ Scuti stars are in this range. Whereas 50 % of the systems in Figure 28 are found to have 0.055 day periods or less, 85 % of the stars in Figure 29 can be found between the 0.065 and 0.2950 day bins. From these figures it is evident that binarity in close systems may cause a decrease in the mean pulsation period.

4.3 Pulsation Period vs. Orbital Period

The original relationship found by [1] was reported as

$$P_{pulse} = 0.020(2)P_{orb} - 0.005(8) \tag{4.1}$$

where the parentheses represent the uncertainty in the last digit. A total of 20 systems were used to obtain the relationship. A correlation coefficient of 0.89 was found and quoted as 'highly significant'. Of these, 17 have less than a four-day orbital period. To verify a relationship as given by [1] an expansion to include systems beyond the 4 day mark is needed. Fortunately, through the various observing campaigns searching for pulsating stars in close binary systems this deficiency has been addressed, including three discovered by myself; SY Cen, QY Aql, EY Ori, and one discovered by Ronald Kaitchuck, FO Ori. From the data in Table 2, it can be seen that of the 41 systems used for analysis, 14 systems are above four-day orbital



Figure 31. Pulsation period vs. orbital period. Note EY Ori and FO Ori as outliers.

periods. This is on the order of 30% of the systems. This is compared to 15% of the original study by [1]. The pulsation periods found in Table 3 were plotted against the orbital period in Figure 31.

If, based on Figure 31, we take EY Ori and FO Ori as outliers and calculate the leastsquares fit using the remaining 28 systems; the linear trend is given as:

$$P_{pulse} = 0.014(2)P_{orb} + 0.011(8) \tag{4.2}.$$

The correlation coefficient for this relationship is 0.82. For 28 measurements, this corresponds to a $Prob_N(|r| \ge |r_o)$ of less than 0.1 percent. A relationship is considered *significant* below five percent and *highly significant* below one percent (Taylor, 1997). If EY Ori and FO Ori are included, the coefficient value drops to 0.45. For 30 systems, this gives a probability below 2.9%, indicating the relationship is significant, but not as highly so.

Whereas the sample in [1] had only three systems above the 4 day mark for the orbital period, the relationship given in eq. 4.2 utilized 11 systems above the four day threshold (13 if FO Ori and EY Ori are included). This should therefore be a good indicator as to the true nature of a trend if one does indeed exist.

The additions of EY Ori and FO Ori into the sample population give interesting tests for points beyond the 10 day mark (if we exclude these two points, the r value increases to 0.88, a significant increase). If the systems under the 10 day mark represent physical altering of the pulsation period by (presumably) the proximity of the pulsating component to its companion, then examination of the positions of EY Ori and FO Ori on the plot would lead to different possible conclusions. First, it could mean the relationship exists under the 10 day orbital period and these two objects are spurious. Second, the mechanism responsible for altering the pulsation period may weaken and a different relationship, possibly non-linear, holds beyond 10 days to some unknown orbital period, beyond which we should be able to assume the components evolve more or less as individual stars. A third possibility is that any physical mechanism ceases to work after about the 10 day orbital period and the pulsations are unaffected. Fourth, the pulsations may not be physically altered by the presence of a companion and the effect we see up to the 10 day mark is simply spurious. The fifth possibility is that the orbital period, being dependent on other fundamental quantities, is not the parameter that should be sought to describe the influence of pulsation periods. To investigate these possibilities further, we turn next to the gravitational potential in the system.

4.4 Potential and Pulsation

In an effort to find a more fundamental relationship between the pulsation period and the influence of a close companion, gravitational potential was investigated. Using the Roche approximation (discussed in 2.1.2) for the distance from the center of the star to a point on the surface in the y-direction (with the stars in the x-y plane), a formula for the potential on that point was derived. As the surfaces of the stars are equipotentials, this value will reflect the potential across the surface of the star. Inserting the Roche approximation into the equation for potential yields:

$$\Phi = -G(\alpha + \beta) - \frac{1}{2} \left[a^2 (\gamma^2 + \xi^2) \right] \omega^2$$
(4.6)

where $\alpha = M_1/(a \xi)$, $\beta = M_2/[a(\xi^2+1)^{1/2}]$, $\gamma = M_2/(M_1+M_2)$, $\xi = 0.378q^{0.2084}$, *a* is the semi major axis as expressed by Kepler's Third law, and $\omega = (2\pi)/P$ (see appendix for derivation of eq. 4.6). The pulsation period vs. the potential is plotted in Figure 32. As with the pulsation period vs. orbital period relationship, there seems to be a weak correlation between the potential and pulsation period (in calculating the potential, the minus sign in eq. 4.6 was ignored in order to be able to take the logarithm). The deeper the surface of the pulsating star is in a potential well the shorter the pulsations are, in general.

Of the systems in Table 3 whose masses were given in Table 2, 25 were available for analysis. Again, a glance at the graph indicates FO Ori to be an outlier (interestingly, EY Ori is not an outlier here) along with AB Per. Taking this as the case and only using the other 23 systems, a fit is given as:

$$\log P_{pulse} = -0.87(15) \log \Phi + 1.56(50) \tag{4.7}$$



Figure 32. Pulsation period vs. the potential on the surface of the primary.

with a correlation coefficient of 0.82 was found. This correlation is below the one percent value for $Prob_N(|r| \ge |r_o)$ and can be considered highly significant. To see if the relationship tightens, one possible line of further investigation would be to determine the potential at a point at the equilibrium position of the ionization zone responsible for the pulsations. To do this, detailed knowledge of where the zones are for each star would be necessary. Presumably one would be able to obtain a reasonable estimate based on the type of pulsation (radial vs. non-radial) and the mode(s) in which the star pulsates. Because no modal identification was attempted in this study, this was not pursued.

4.5 Roche Lobe Filling

As described in section 2.1.2 the Roche geometry of a binary system is of fundamental importance in describing the physical characteristics of the system. Figure 33 shows the pulsation period as a function of percentage of Roche Lobe filled. RL% is the percent of the Roche Lobe filled (data taken from Table 2). The graph shows 25 data points. Inspection shows three significant outliers, FO Ori, AS Eri, and RZ Cas. FO Ori, can justifiably be excluded from this analysis due to its separation and high mass ratio (q = 0.68). The components of this system should not be significantly distorted from spherical symmetry. AS Eri can justifiably be ignored due to its low mass ratio (q=0.11). The pulsating component in this system is much more massive than its companion. It should therefore not have a significant departure from spherical symmetry. RZ Cas is a slightly harder system to justify excluding. The system has a mass ratio of q = 0.34. This is not significantly small. Also, the close proximity due to the short orbital period lends to more Roche Lobe filling than FO Ori, for example.

However, the relationship shows a much higher correlation excluding these systems, enough so that exclusion may be justified on statistical grounds alone. Using the remaining 12 systems a relationship of:

$$\log P_{pulse} = -1.15 (18) \log (RL\%) - 0.62(30)$$
(4.8)

was found. The relationship has a correlation coefficient of 0.82. This yields a $Prob_N(|r| \ge |r_o)$ below the 0.05% level, indicating a highly significant relationship. If the other three data points are included, the correlation coefficient drops to 0.48, indicating a $Prob_N(|r| \ge |r_o)$ just above the 1% level, indicating a significant, albeit to a lesser degree, relationship.



Figure 33. Pulsation period vs. the percent of the Roche Lobe filled by the pulsator.

4.6 Force and Pulsation

The other relationship [1] investigated was how the force of the companion on the surface of the pulsator affected pulsation. In order to do so, the authors plotted the force per unit mass the companion exerts on the surface of the pulsating star. In their initial study, only eight systems were used. Nonetheless, a fairly strong correlation was found. One thing to note is this model did not take into account Roche distortion, but treated the pulsating variables as spheres. This assumption may be a valid assumption, at least to first order. Several of the systems in Table 2 are included in the compendium *Binary Stars: A Pictorial Atlas* (Terrell, Mukherjee, Wilson, 1992). Included are VV Uma, R CMa, X Tri, AS Eri, Y Cam, and QY Aql. The book gives values for the interesting points on the surface of each star after calculating the Roche distortion (the points of interest are points closest and farthest from the secondary along

the axis of revolution, along with the points on the surface in the y and z directions as seen facing the orbital plane). Solutions to the systems were aided by code developed by Wilson & Devinney (1971). In each case the pulsating star is found to deviate from spherical symmetry less than ten percent (in most cases, less than five). This could indicate that a spherical approximation for δ Scuti pulsators in detached and semi-detached systems, especially for oEA's, is a valid assumption. Because the δ Scuti is generally the more massive object in oEA systems, the spherical structure will not be greatly affected by the proximity of a less massive companion (this is essentially the same argument used for not including AS Eri above).

The study of [1] investigated the force on the surface of the pulsator due to the companion per unit mass of the pulsator. In equation form, the force is calculated as

$$\frac{F}{M_P} = \frac{GM_C}{d^2} \tag{4.9}$$

where d is the distance from the center of mass of M_c to the surface of M_P (M_p and M_c indicate the mass of the pulsator and companion respectively; for most cases $M_p=M_1$ and $M_c=M_2$ from Table 2). Using the given spherical radii from [1], we have $d = a - R_1$ and eq. 4.9 becomes

$$\frac{F}{M_{P}} = \frac{GM_{C}}{(a-R_{1})^{2}}$$
(4.10)

with *a* being the semi major axis. The number of systems is extended to 25 and the results are shown in Figure 34. Again, FO Ori and AS Eri are outliers in the data ([1] excluded AS Eri from their force analysis). Excluding these from the analysis, a relationship of

$$\log P_{pulse} = -0.460(70) \log (F/M_P) - 1.261(38)$$
(4.11)



Figure 34. The pulsation period vs. the force of the companion on the surface of the pulsator. was found while the correlation coefficient for the data is 0.86, indicating a highly significant relationship (if we include FO Ori and AS Eri, the relationship drops to the significant level, but is still below the 5% value). The authors of [1] allude to the idea that this relationship may indicate tidal forces at work in driving the pulsations. This however, leads to a paradox: if the pulsations are driven by constant tidal effects then the star should diverge from spherical symmetry. And if the star is no longer spherical, then taking the non-spherical structure into account should provide a tighter relationship. Because of this paradox, it is herein proposed that, if the force of the companion on the pulsator is the driving mechanism for influencing pulsation periods, one should look at the pulsation equilibrium position within the star. As shown in section 2.2.3, almost all of the pulsating stars shown in Figure 34 are best described as pulsating in non-radial modes. As described in *Carroll and Ostlie (2007, pg. 497)* the ionization zones which drive the non-radial pulsations are relatively close to the stellar surface. This being the case, as above, if the modes and equilibrium position were identified, one could then calculate the force from the companion at the equilibrium position. If this scenario is indeed the case, then it should not be surprising that Figure 31 shows a strong relationship as, at least to a first order approximation for a given δ Scuti star, the equilibrium position of the ionization zone(s) is roughly equal to the stellar radius. Again, this would require detailed knowledge of the pulsation mode(s) of each star to determine the equilibrium position of the oscillating layers in the ionization zones.

4.7 Resonance

Target	Porb	P _{pulse}	sigma	Porb/Ppulse
CT Her	1.7864	0.018891414	0.000000004	94.5614762
AS Eri	2.6641	0.01694021	0.0000001	157.264913
RZ Cas	1.1953	0.01557790	0.00000005	76.7304906
AB Cas	1.3669	0.0582873	0.000003	23.4510832
Y Cam	3.3057	0.0664587	0.0000004	49.7406365
VV Uma	0.6874	0.019516	0.000003	35.2216886
IU Per	0.8570	0.023751	0.000005	36.082271
Al Hya	8.2897	0.138031	0.000006	60.0570164
HIP 7666	2.3723	0.04088	0.00001	58.0335749
TW Dra	2.8069	0.05559	0.00006	50.496131
IV Cas	0.9958	0.03058819	0.0000007	32.5550521
HD 172189	5.7020	0.0510272	0.0000002	111.744375
V577 Oph	6.0791	0.069491	0.000004	87.4800727
BG Peg	1.9524	0.0400229	0.0000002	48.7820807
RR Lep	0.91543	0.0313820	0.0000003	29.1705431
WY Leo	4.9859	0.0655617	0.0000004	76.0489355
AC Tau	2.0434	0.057035	0.000003	35.8269322
MX Pav	5.730835	0.07560166	0.0000006	75.8030268
IZ Tel	4.880219	0.0737572	0.0000001	66.1660434
VY Mic	4.436373	0.0817387	0.0000002	54.2750797
Y Leo	1.6861	0.0289995	0.0000005	58.1424102
X Tri	0.9715	0.022	0.0001	44.1590909
FO Ori	18.8006	0.0286	0.0001	657.363636

Table 5. The P_{orb}/P_{pulse} ratios are calculated for the systems whose uncertainties are known to a high degree.

Several papers have alluded to certain systems having a close-to-integer ratio between the orbital period and pulsation period and it has been suggested there is a mechanism for causing this resonance. Investigating resonances involves determining both the orbital period and pulsation period to a very high degree of accuracy. As a result, of the 30 systems for which uncertainties are available, 22 systems were known to a high enough precision to carry out the analysis. The results are shown in Table 4. As can be seen, only a handful of systems are less than 1/10th of an integer away from a whole number. Tsvetkov and Petrova (1993) noted that Porb/Poulse was very nearly 50, 20, and 60 for Y Cam, RS Cha, and AI Hya respectively. The P_{orb}/P_{pulse} values they give are 49.74, 19.88, and 60.06, respectively. However, no claim as to what 'is nearly' and what is not is given. Obviously of these three AI Hya is the closest to an integer multiple, and yet Y Cam is also put in this class at 49.74. This is 0.26, or 26 % away from the closest integer value. This leads to an estimated range of 52% (26% each way of an integer value) at which the ratio would be considered 'close' (for example, if the value of the ratio was found to be between 25 and 26, everything from 25.0-25.26, and 25.74 and 26.0 would be included in the range at which it would be considered 'close' to an integer). Because this is a rather large percent of the range between integers, I have only included values that are within 1/10th of an integer value for analysis. Of the 22 systems in Table 4, four have P_{orb}/P_{pulse} ratios below the 1/10th integer value. This is on the order of about 18%. Because only a very few of these systems seem to be in some sort of resonance, it is concluded that while resonance may occur in some systems, it is not a uniform phenomena that can be predicted by placing a δ Scuti star in a close binary system alone. Further investigations into specific modes may however prove an interesting line of research. It may be eventually shown that a resonance mechanism

does play a role for specific pulsation modes. Until more theoretical and observational groundwork is laid, however, this aspect remains a conspicuous question mark as to whether it is a predictable effect or if this is coincidence.

4.8 Pulsation Period vs. Orbital Parameters without Uncertainties

The relationships derived earlier are now generalized without the uncertainties on the pulsation periods attached. This is done to serve as a check for both the results above and to compare with similar procedures in the literature (notably that of [1]) where many relationships are derived without uncertainties attached. In general this should be a valid assumption as to report a discovery in refereed literature one should have enough cycles to determine the period to a high degree of accuracy.

We begin by plotting the pulsation periods vs. orbital periods for all of the systems in Table 2. The results are shown in Figure 35 where over 40 systems were used in the analysis. As done earlier, FO Ori and EY Ori are taken to be outliers. The data were fit to give a relationship of:

$$P_{pulse} = 0.013(2) P_{orb} + 0.018(6) \tag{4.12}$$

with a correlation coefficient is 0.79. This is highly significant. If EY Ori and FO Ori are included in the analysis, the correlation coefficient drops to 0.45, yet for 40 systems this is still below the 1% level and is significant. On the other hand, the slope decreases to 0.0042, almost 1/3 of the given slope above, which is a very significant change.

As noted above, several interpretations arise when looking at this graph. First, note the slope is less steep than that given by [1]. The notable outlier on Figure 35 is AB Per. The first interpretation is similar to above, that a physical relationship exists for binaries with periods



Figure 35. Pulsation periods vs. the orbital periods.

less than 10 days. As was the case with the plot generated by [1] and the four-day orbital period, more systems between the 10 and 18-day orbital period would be needed. A second interpretation is that, as the slope did decrease significantly, that no true relationship between the orbital period and pulsation period exists. The hypothesis is that as more pulsating stars in binaries in the 10 to 18 day range are found, the closer to zero the slope becomes. If this becomes the case, it can be concluded that if binarity affects the pulsation period, then the orbital period is not the fundamental quantity to be interested in.

The second parameter investigated is the pulsation period vs. the potential on the surface of the pulsator. Figure 36 shows the pulsation period as a function of the potential. As done earlier, of the 34 systems used, FO Ori was excluded due to being the largest outlier. The fit relationship is given as:



Figure 36. Pulsation period as a function of potential on the surface of the pulsator.

$$\log P_{pulse} = -0.90(13) \log \Phi + 1.70(43) \tag{4.13}$$

and the correlation coefficient is 0.78. This places the probability below 1 percent, indicating a highly significant relationship. Inclusion of FO Ori in the data causes the slope to increase from -0.90 to -0.68 and the correlation coefficient decreases from 0.76 to 0.64, still in the highly significant regime.

Even with FO Ori as an outlier, there seems to be at least a weak trend in the data and although there isn't an apparently strong mathematical trend, the linear fit seems to be the best according to the data. Again, perhaps the relationship could be tightened when the potential well the ionization zone is in could be determined to higher accuracy.

Next, the Roche Lobe filling was examined. Figure 37 shows the pulsation period as a function of the Roche Lobe filling. As was done previously, FO Ori and AS Eri and RZ Cas are left



Figure 37. Pulsation period as a function of percentage of Roche Lobe filled. out to be consistent with procedure. The fit for the relationship is:

$$\log P_{pulse} = -0.99(16) \log (RL\%) + 0.37(27)$$
(4.14)

with a correlation coefficient of 0.76, indicating high significance. This data set utilized 31 systems. Including FO Ori, AS Eri, and RZ Cas, the slope increases from -0.99 to -0.56 while the correlation coefficient drops to 0.45, still at the significant level. Inspection of Figure 34 does seem to indicate a general trend that as the percent the Roche Lobe is filled, the shorter the pulsations become.

The last parameter investigated is the force on the surface of the pulsator due to the companion. Over 35 systems are used for this analysis, or over four times as many as the relation derived in [1]. Although there are only 34 systems in Table 2, I added a data point for a pulsating star with a close exoplanet, WASP-33b (Herrero et al. 2011). This data point should



Figure 38. Pulsation period vs. force of the companion on the surface of the pulsator.

be interesting; if there is a relationship between the force a companion has on the surface of a pulsating star, is there a minimum mass needed by the companion to trigger the phenomenon? As is shown in Figure 38, WASP-33b falls on the trend nicely. Again, FO Ori, AS Eri, and RZ Cas are the outliers. Thus for the 32 remaining systems the fit was found to be:

$$\log P_{pulse} = -0.38(5) \log (F/m) - 1.22(3) \tag{4.15}$$

where the correlation coefficient is found to be 0.79, indicating a high level of significance. If the three outliers are included, the slope increases to 0.27(7) and the correlation coefficient drops to 0.55. The uncertainties in both slopes overlap, as such there is no significant difference between the two models, only a slightly better fit, however both are highly significant.

4.9 Summary of Results

All of the above relationships seek to determine if orbital parameters of close binary systems affect stellar pulsation. Two methods and thus two different calculations have been performed for each parameter. These are the orbital period, gravitational potential, percent of Roche Lobe filled, and force per unit mass on the pulsator's surface due to the companion. In this section the results are summarized and presented in Table 5. Presented in the table are the slopes and uncertainties for each fit and the correlation coefficients for each. Method 1 represents the linear fits with uncertainties, and Method 2 is the fit without.

	Slo Me	Correlation Coeff Method			
Relationship	1	2	1	2	
P _{pulse} vs. P _{orb}	0.014 <u>+</u> 0.002	0.013 <u>+</u> 0.002	0.82	0.79	
log P _{pulse} vs. log Φ	-0.87 <u>+</u> 0.15	-0.90 <u>+</u> 0.13	0.82	0.78	
log P _{pulse} vs. Log RL%	-1.15 <u>+</u> 18	-0.99 <u>+</u> 0.16	0.82	0.76	
log P _{pulse} vs. log F/M _p	-0.46 <u>+</u> 0.07	-0.38 <u>+</u> 0.05	0.86	0.79	

Table 6. Summary of the fit relationships for each method and correlation coefficients.

Inspection of Table 5 reveals consistency between the slopes of the methods. This indicates the possible validity of the given relationships as in each case a significantly greater number of data points for Method 2 than Method 1. The two relationships with the lowest uncertainties and highest correlation coefficients are the P_{orb} and F/M_P .

4.10 Theoretical Considerations

If a relationship between the pulsation period and various orbital parameters exists then one would be inclined to see if the relationship(s) could be derived analytically. From section 2.2.1 it was shown that the pulsation period for an isolated star is related to the pulsation constant and the mean density of the pulsating star. The mean density is dependent on the mass of the pulsator. In the cases of the orbital period, potential, and force, each had explicit expressions involving the mass of the pulsator. These equations could be solved for the mass of the pulsator and these expressions inserted into the Period-mean density relationship. Because the relationship involves a ratio of the density of the sun to the pulsators density, it can be written as:

$$\Pi = Q_{\sqrt{\frac{\overline{\rho}_{sun}}{\overline{\rho}}}}$$
(4.16)

and because the relationships above were given in solar units, the expression can be rearranged to the form:

$$\Pi = Q_{\sqrt{\frac{R_p^3}{M_p}}} \tag{4.17}$$

If Kepler's Third law is solved for the mass of the pulsating star and this is inserted into equation 4.17, we obtain:

$$\Pi = PQ \left[\frac{R_P^{\ 3}G}{4\pi^2 a^3 - M_s P^2 G} \right]^{\frac{1}{2}}$$
(4.18).

After some rearrangement and substituting Kepler's Third law again to eliminate the orbital period in the denominator, we arrive at:

$$\Pi = PQ \left[\frac{R^3 G}{4\pi^2 a^3} \right]^{\frac{1}{2}} \left[1 - \frac{M_s}{M_p + M_s} \right]^{-\frac{1}{2}}$$
(4.19)

at which point one might be tempted to perform a Taylor series on the last term in order to attempt to obtain an equation of the usual form y = mx + b with P being the independent variable. However, two observations render this reasoning invalid. First, in order to perform a Taylor series on an expression of the form $[1-x]^{-1/2}$, x must be a small number (generally below $\frac{1}{2}$). This isn't necessarily the case, as here, M_P and R_P designate, from equation 4.17, the mass and radius of the pulsating star and $M_{\rm S}$ designates the mass of the companion. Of the systems in Table 2, four of the pulsators are thought to be the cooler component. These are AI Hya, RS Cha, WY Leo, and WY Cet. Of these four, three of them have the companion's mass larger than the pulsator's mass. This leads to a term larger than $\frac{1}{2}$. So the Taylor series is, in general, an invalid technique here. Secondly and more importantly, while equation 4.19 does seem linear in P, it turns out that, for a given pulsation constant (i.e. for a given pulsation mode), equation 4.19 gives a horizontal line. This is due to the conspicuous a^3 in the denominator of the second factor. If we take it out of the brackets, we get a $P/a^{3/2}$ term, which, by Kepler's Third law, is equal to constants for a given set of masses. This implies that if binarity affects pulsation, it does more so than simple consideration of how the period-mean density relation is related to orbital parameters through the pulsator's mass.

One line of reasoning is that some orbital parameter alone is not what is affected, but binarity also affects the pulsation mode(s), therefore affecting the Q value. If this is the case, this might help explain much of the scatter present in each of the figures given above. Perhaps separate and tighter relationships exist for each given pulsation mode, but because photometrically detectable modes are all low-order (n=1, 2, 3, etc...; ℓ =1, 2, etc...) these provide periods close enough to provide what appear to be weak relationships. If it could be found that
binarity affects Q, it would be interesting to reformulate all of the relationships given above to see if/how much tighter each one is.

From this it can be concluded that deeper theoretical arguments need to be formulated and investigated, leading to the fact that more observations would then be needed. For theoretical models to be checked with high precision, all of the parameters of each system would need to be known to a high precision as well. This means observations that would yield mass ratios and therefore masses where errors would likely be on the order of a few percent or less. Likewise pulsation modes (also dependent on the mass and radius of the pulsating star) would need to be known extremely accurately as well (while improvements in this area are being made, the precision needed may not be there yet).

5. Conclusion

This thesis has sought to explore how a close companion might influence stellar pulsations of δ Scuti stars. This work sought to further that of [1] which introduced an empirical relationship between the pulsation period and orbital period and also explored how the force on the surface of the pulsator due to the companion may influence the pulsation period. Both show the same general result; as the pulsation period increases and thus the force decreases, the pulsation periods are observed to increase. The pulsation period vs. orbital period from [1] involved 20 systems with a fit of P_{pulse} = -0.020(2) P_{orb} – 0.005(8) with a correlation coefficient of 0.89. However, of the 20 systems, only 3 had orbital periods above 4 days. The authors of [2] also introduced a catalogue of potential targets for pulsating variables in close binary systems, or so called oEAs.

In an effort to further explore the possible connections between orbital parameters and pulsation, I have used the data from [1], collected results from other campaigns for oEAs, and observed several targets from the catalogue of [2]. This resulted in the discovery of 6 new variables from my own campaign. Each variable had more than one night of usable data except for SY Cen, which only one night of data was able to be gathered. Further observations on each object are encouraged to precisely determine the pulsation period(s) and possible modes of oscillation.

From these observations and the collections from the literature, a total of 40 systems were available for analysis. The first step was construct a histogram of orbital periods binned in increments of 0.01 days for oEAs and compare these to the pulsation periods for single δ Scuti stars. This shows that a large percentage of oEAs have pulsation periods below the average that of single δ Scuti stars. This indicates that any subsequent relationships found may be real. Next, to gain a sense of how accurate any relationships found may be, only pulsation periods with known uncertainties were taken into consideration. Each relationship was also then extended to include all systems for which the pertinent information was available. In each case, the slopes for each relationship agree between the two methods. However, these slopes depend on excluding outliers in each case. For the P_{pulse} vs. P_{orb} relationship, FO Ori and EY Ori were the outliers, and not taken into consideration. Interestingly, while FO Ori remained an outlier in every other analysis, EY Ori did not (AS Eri was also a significant outlier, also noted by [1]). This leads to the conclusion that if binarity affects pulsation periods, then the orbital period is not the fundamental parameter to look at. The other relationships developed were the potential, percentage of Roche Lobe filled by the pulsator, and force per unit mass on the pulsator's surface. In each case, the correlation coefficients were considered either significant or highly significant, yet to varying degrees. Other references indicate that certain systems seem to be in a resonance between the orbital period and pulsation period. However, this was shown to not be a uniform outcome of pulsations in close systems. At first glance, resonance seems more of a coincidence than any physical mechanism. However, to determine more

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certainly, more theoretical advances need to be made. To this end as well, it was shown that theoretical arguments need more taken into account than simply using the period-mean density relation and orbital parameters in terms of the pulsators mass to derive possible relationships. On the observational side, more data from which precise orbital periods and pulsation modes can be determined needs to be taken to test theoretical models as they are developed. It may turn out that each of the orbital parameters explored depends on the mode of pulsation and could therefore tighten the relationships developed.

This line of research is important in the realm of stellar astrophysics. Both types of systems (pulsating variables and eclipsing binaries) provide ways to determine certain properties of their respective constituents. Investigation of pulsating variables, especially if the mode(s) can be identified, provides a probe into the interior. This helps provide valuable checks for the theory of stellar interiors. On the other hand, eclipsing binary systems provide valuable quantities such as the mass and radius of each component in the system. These data together should provide new tools for theoretical advances and provide constraints on the physical parameters of pulsating variables.

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Appendix

A.1 Conversion of Newton's Gravitational Constant

This section details the conversion of Newton's Gravitational Constant, G, from the familiar S.I. units to the more useful units for binary star astronomy. The unit of time in S.I. is the second (s), mass is the kilogram (kg), and distance is the meter (m). We need to convert these to units of 1 day for time, 1 M_{SUN} for mass and 1 R_{SUN} for distance.

In S.I. units, $G = 6.67 \times 10^{-11} \text{ N m}^2 / \text{kg}^2$. N can be expressed in terms of m, kg, and s as N=kg m/s². This gives G=6.67×10⁻¹¹ m³/kg s². Now 1 R_{SUN} = 6.955×10⁸ m, 1 M_{SUN} = 1.989×10³⁰ kg, and 1 day = 86400 s. Using these values gives

$$G = 6.67 \times 10^{-11} \frac{m^3}{kg * s^2} \left(\frac{R_{SUN}}{6.955 \times 10^8 m}\right)^3 \left(\frac{1.989 \times 10^{30} kg}{M_{SUN}}\right) \left(\frac{86400 s}{day}\right)^2 = 2943.7 \frac{R_{SUN}^3}{M_{sun} * day}$$
(A.1)

A.2 Derivation of Gravitational Potential



Figure A.1. Diagram of a two-body system with Roche distortion.

Our goal is to calculate the gravitational potential on the surface of the primary star. The situation is complicated by the fact that often in close systems, the stars are often deformed from spherical symmetry. The mathematical analysis to describe the non-spherical deformation was initially carried out by Roche (). The gravitational potential is described by equation 2.(). There is an approximation for the distance from the center of a deformed star to the surface on the y-axis. We want to calculate the potential on the surface of the pulsator, arbitrarily labeled M_1 , assumed to be the more massive component. The distance from the center of M_1 to the surface on the y-axis is labeled S_1 . The distance from the point of the test mass to the center of the other component is S_2 , and the distance from the test mass to the center of mass (cm) is labeled 'r'.

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To derive the potential, we start with several well-known equations for two-body systems. The potential itself is as:

$$\Phi = -G\left(\frac{M_1}{S_1} + \frac{M_2}{S_2}\right) - \frac{1}{2}r^2\omega^2.$$
 (A.2)

We need expressions for S_1 , S_2 , r, and ω in terms of what we can either observe or derive from observables, namely P, G, M_1 , M_2 , and a. To that end, we use several well-known relationships.

The relationships used are $M_1r_1=M_2r_2$, $r_1+r_2=a$, and Kepler's Third law, which states

$$P^{2} = \frac{4\pi^{2}}{G} \frac{a^{3}}{(M_{1} + M_{2})}.$$
 (A.3)

From Table 2, we've been giving the orbital periods and masses of the components for several of the systems. From this it is straightforward to calculate the semi-major axis, *a*. The approximation for the distance from the center to the surface on the y-axis is given as (denoted by S_1) $S_1 = a0.378q^{0.2084}$ where *q* is defined as the mass ration, M_1/M_2 . To simplify, let $\xi = 0.378q^{0.2084}$, thus $S_1 = a\xi$. r and S_2 can both be calculated by the Pythagorean Theorem: $r^2 = (S_1^2 + r_1^2)$ and $S_2 = (S_1^2 + a^2)^{1/2}$. We first look at r_1 .

Rearranging the two equations above, and solving each for r2, we have

$$r_2 = a - r_1$$
, and $r_2 = \frac{M_1 r_1}{M_2}$. (A.4, A.5)

Combining these and solving for r_1 yields

$$r_1 = \frac{a}{q+1}.\tag{A.6}$$

We can now calculate *r* in terms of the quantities we're interested in. From the Pythagorean Theorem above, we have

$$r^{2} = (a\xi)^{2} + (\frac{a}{q+1})^{2}$$
(A.7)

and rearranging yields

$$r^{2} = a^{2} (\xi^{2} + (\frac{1}{q+1})^{2}).$$
(A.8)

We know look at S_{2} . Again, from the Pythagorean Theorem we have

$$S_2^2 = S_1^2 + a^2 \tag{A.9}$$

and rearranging gives

$$S_2^2 = (a\xi)^2 + a^2$$
 (A.10)

$$S_2^2 = a^2(\xi^2 + 1) \tag{A.11}$$

$$S_2 = a(\xi^2 + 1)^{1/2}.$$
 (A.12)

We now use the fact that $\omega = \frac{2\pi}{P}$, and with this relationship, we're ready to substitute all the

quantities we've obtained into the expression for the gravitational potential.

$$\Phi = -G\left(\frac{M_1}{a\xi} + \frac{M_2}{a(\xi^2 + 1)^{1/2}}\right) - \frac{1}{2}\left[a^2\left(\xi^2 + \left(\frac{1}{q+1}\right)^2\right)\right]\left(\frac{2\pi}{P}\right)^2$$
(A.13)

We now let $\alpha = M_1/(a\xi)$, $\beta = M_2/[a(\xi^2+1)^{1/2}]$, and $\gamma = [a^2(\xi^2+(1/(q+1))^2)$ to obtain

$$\Phi = -G(\alpha + \beta) - \frac{1}{2} \left[a^2 (\xi^2 + \gamma^2) \right] \left(\frac{2\pi}{P} \right)^2$$
(A.14)

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