Characterization of Cataclysmic Variables and White Dwarfs in the Kepler Field

by

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Abstract

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by Trisha Doyle

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We present long baseline Kepler photometry and ground-based Hale 200” spectroscopy of five known white dwarfs, five newly identified white dwarfs, and a cataclysmic variable, V523 Lyr. Analysis of the photometric and spectroscopic data is used to characterize the white dwarfs and the cataclysmic variable, by determining preliminary fundamental parameters.

We model the white dwarfs to determine their fundamental parameters, effective temperature and surface gravity. If the effective temperature of a white dwarf falls within a specific range, the white dwarf is expected to be a pulsator. We verified possible pulsation with complementary Kepler light curves when possible. The modeled effective temperatures place one out of our ten white dwarfs in the pulsator regime. Pulsating white dwarfs help to refine the temperature range where pulsations occur and are used to probe their internal structure.

V523 Lyr is hypothesized to be a dwarf nova type cataclysmic variable, which exhibits 28 outbursts over ~1000 days of Kepler data. The outbursts are quasi-periodic and occur approximately every 25 days and last ~9 days. V523 Lyr is hypothesized to be on the rise of an outburst during our spectral observations.
# Contents

Abstract iii  
List of Figures vi  
List of Tables x  
Abbreviations xi  
Acknowledgements xii  

## 1 White Dwarfs and Cataclysmic Variables 1  
1.1 Introduction ........................................ 1  
1.2 White Dwarfs ...................................... 3  
1.3 Cataclysmic Variables ............................... 8  

## 2 Observations and Data Reduction 11  
2.1 Spectroscopic Observations .............................. 11  
2.1.1 Palomar Instruments and Observations .................. 12  
2.1.2 Palomar Data Reduction ........................... 16  
2.2 Photometric Observations ............................... 17  
2.2.1 *Kepler* Observations ............................ 18  
2.2.2 *Kepler* Data Reduction ........................ 21  

## 3 Modeling of DA White Dwarfs 25  
3.1 White Dwarf Pulsations ................................ 25  
3.2 Spectral Modeling .................................... 28  
3.3 Spectral and Photometric Analysis for DA White Dwarfs ....... 31  
3.3.1 PMI18450+4800 (KIC 10709534) ....................... 32  
3.3.2 PMI18486+4811 (KIC 10777440) ....................... 34  
3.3.3 PMI18553+4755 (KIC 10649118) ....................... 36  
3.3.4 PMI19002+3922 (KIC 4242459) ....................... 38
### List of Figures

1.1 One of our blue spectra (left) and red spectra (right), over plotted with the model in red and the blackbody at the estimated effective temperature in blue. .................................................. 4

2.1 Schematic of a blazed grating. .................................................. 14
2.2 Schematic of the *Kepler* 0.95m space telescope. ......................... 18
2.3 The *Kepler* field overlaid on the Milky Way Galaxy. ................... 19
2.4 Top left: Example output of `keppixseries` showing the raw light curve of each pixel. Greyed boxes show the aperture used for the pipeline-reduce light curves. Top right: Example output of `kepfield` displaying all the known sources within this particular field. Green circles denote KIC sources, with larger circles corresponding to brighter objects, and red circles denote non-KIC sources. Bottom: Example of the GUI (graphical user interface) for `kepmask`, where the green box represents the pixel which was chosen for the mask. .............................................. 23

3.1 Evolutionary diagram of a 13 Gyr old star with the instability strips over plotted on the evolutionary track. .................................................. 27
3.2 PMI18450+4800 blue spectrum with best fit model overlaid in red. ....... 33
3.3 PMI18450+4800 red spectrum with best fit model overlaid in red and the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line. .......................................................... 34
3.4 PMI18486+4811 blue spectrum with best fit model overlaid in red. ...... 35
3.5 PMI18486+4811 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line. .......................................................... 36
3.6 PMI18553+4755 blue spectrum with best fit model overlaid in red. ...... 37
3.7 PMI18553+4755 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line. .......................................................... 37
3.8 PMI19002+3922 blue spectrum with best fit model overlaid in red. ....... 39
3.9 PMI19002+3922 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a blue dotted line. .......................................................... 39
3.10 PMI19002+3299 long cadence light curve spanning 17 quarters. ........ 40
3.11 PMI19002+3922 short cadence light curve spanning 8 quarters. 

3.12 NEA Lomb-Scargle plot of power versus period for PMI19002+3922, which does not show strong periodicity in the range of expected pulsation periods (<1 day). 

3.13 PMI19085+4338 blue spectrum with best fit model overlaid in red. 

3.14 PMI19085+4338 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line. 

3.15 PMI19141+4936 blue spectrum with best fit model overlaid in red. 

3.16 PMI19141+4936 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line. 

3.17 PMI19141+4936 long cadence light curve spanning 5 quarters. 

3.18 PMI19141+4936 short cadence light curve spanning 1 quarter. 

3.19 PMI19141+4936 phased long cadence light curve. 

3.20 NEA Lomb-Scargle plot of power versus period for PMI19141+4936, which shows extremely strong periodicity at 4.89 days. 

3.21 PMI19173+4452 blue spectrum with best fit model overlaid in red. 

3.22 PMI19173+4452 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line. 

3.23 PMI19173+4452 long cadence light curve spanning 6 quarters. 

3.24 PMI19173+4452 short cadence light curve spanning 2 quarters. 

3.25 NEA Lomb-Scargle plot of power versus period for PMI19173+4452, which does not show strong periodicity in the range of expected pulsation periods (<1 day). 

3.26 PMI19179+4524 blue spectrum with best fit model overlaid in red. 

3.27 PMI19179+4524 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line. 

3.28 PMI19245+3734 blue spectrum with best fit model overlaid in red. 

3.29 PMI19245+3734 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a blue dotted line. 

3.30 PMI19245+3734 long cadence light curve spanning 4 quarters. 

3.31 NEA Lomb-Scargle plot of power versus period for PMI19245+3734, which does not show strong periodicity in the range of expected pulsation periods (<1 day). 

3.32 PMI19409+4240 blue spectrum with best fit model overlaid in red. 

3.33 PMI19409+4240 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line. 

3.34 PMI19409+4240 long cadence light curve spanning 3 quarters.
3.35 PMI19409+4240 short cadence light curve spanning 1 quarter. 58
3.36 NEA Lomb-Scargle plot of power versus period for PMI19409+4240, which does not show strong periodicity in the range of expected pulsation periods (<1 day). 58

4.1 Artists rendition of a cataclysmic variable system’s mass transfer via an accretion disk. Image credit: STScI. 63
4.2 Typical Roche lobe geometry for an semi-detached binary system and the location of the Lagrangian points (Frank, King & Raine, 1985). 64
4.3 Light curve of V523 Lyr, figure 3 from Kaluzny et al. (1997). 67
4.4 Light curve of V523 Lyr, figure 4 from Mochejska et al. (2003). 67
4.5 Finder chart from SDSS with the locations of V523 Lyr and V516 Lyr labeled. 68
4.6 A zoomed in view of V523 Lyr and its location on the pixel file. The red circles are 4 non-KIC sources which are very close to V523 Lyr and could be contaminating its light curve. 69
4.7 V523 Lyr is pointed out on this source image to show that it is not contained within the TPF itself. The dotted line is the boundary of the pixel file and the blue solid line is the original aperture used to extract the pipeline light curve. 71
4.8 Full normalized LC light curve of V523 Lyr from quarter 6 to 16. 74
4.9 V523 Lyr short cadence light curve for quarters 9 and 15. The data has been filtered with a low bandpass to smooth it out in order to see features more clearly. 75
4.10 Example of the quiescent parts of the V523 Lyr light curve (from Q7). 76
4.11 U Gem (left) and SS Cyg (right) outbursts scaled down to compare the shape against outburst number 5 from our V523 Lyr light curve. The x-axis only applies to the V523 Lyr light curve. 76
4.12 SS Cyg outbursts compared to three different outbursts of V523 Lyr (outburst 5 (top left), 6 (top right) and 7 (bottom)). The x-axis only applies to the V523 Lyr light curve. 77
4.13 Comparison of full outburst magnitudes for the two outbursts of SS Cyg show that SS Cyg has a much larger change in magnitude at outburst (~3.5 mags) than V523 Lyr exhibits (< 1 mag). The x-axis only applies to the V523 Lyr light curve. 77
4.14 Stacked blue spectra of V523 Lyr from both nights of observations in chronological order from top to bottom. The red dotted lines, from right to left, show the positions of Hβ, Hγ, and Hδ. 80
4.15 Summed spectrum of all the observations taken on the night of 01 Jul 2013. Emission cores can be seen in Hγ and Hδ. 81
4.16 Summed spectrum of all the observations taken on the night of 02 Jul 2013. Emission cores can be seen in Hγ and Hδ. 81
4.17 An example of a red spectrum of V523 Lyr from 01 Jul 2013. The red dotted line is the wavelength at which Hα occurs. 82
4.18 The corresponding red spectrum for the 02 Jul 2013 blue spectrum, which shows Hβ in emission. The red dotted line denotes the position of Hα.

4.19 Time evolving spectra of dwarf nova, SS Cyg, from quiescence, at the bottom, to maximum outburst, at the top (Warner, 1995).
List of Tables

1.1 Reproduced table of WD spectral type characteristics from Sion (1986) with additions from Oswalt (2013). ........................................ 6
1.2 Hydrogen Balmer series transitions for absorption lines used in modeling WDs, adapted from Carroll & Ostlie (2007). .................. 8
1.3 Summary table of CV types. ............................................. 9
2.1 Table of spectroscopic observations of WDs and V523 Lyr. ...... 16
2.2 Table of WD photometric data. ......................................... 20
2.3 Table of photometric observations of V523 Lyr .................. 21
2.4 Summary of the function of each PyKE task used in this thesis. .. 22
3.1 Table of modeled DA white dwarf parameters derived from the blue spectra. 32
3.2 Order of magnitude estimates of WD cooling ages. ................ 61
4.1 Table of outburst measurements of V523 Lyr. ..................... 72
4.2 Table of spectroscopic observation timing of V523 Lyr. .......... 78
5.1 Results table of DA white dwarfs. .................................. 87
Abbreviations

CAF  Custom Aperture File
CCD  Charge Coupled Device
CN   Classical Nova
CV   Cataclysmic Variable
DBSP Double Beam SPectrograph
DN   Dwarf Nova
FFI  Full-Frame Image
GO   Guest Observer
HST  Hubble Space Telescope
IRAF Image Reduction and Analysis Facility
KIC  Kepler Input Catalog
LC   Long Cadence
MAST Mikulski Archive for Space Telescopes
NASA National Aeronautics and Space Administration
NEA  NASA Exoplanet Archive
NL   Nova Like
PDCSAP Presearch Data Conditioning Simple Aperture Photometry
RN   Recurrent Nova
SAP  Simple Aperture Photometry
SC   Short Cadence
SDSS Sloan Digital Sky Survey
STScI Space Telescope Science Institute
TOAD Tremendous Outburst Amplitude Dwarf nova
TPF  Target Pixel File
UV   UltraViolet
WD   White Dwarf
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Trisha Doyle
Melbourne, FL
May, 2015
I would like to dedicate this to my Uncle Ronnie, for being healthy for over a year now. We look forward to celebrating your life for many more years to come.
Chapter 1

White Dwarfs and Cataclysmic Variables

1.1 Introduction

This thesis presents high precision, high cadence photometric observations made by the Kepler spacecraft of one previously known cataclysmic variable, V523 Lyr, 5 previously identified white dwarfs, and 5 newly discovered white dwarfs. We also present contemporaneously obtained ground-based optical spectroscopy from the Mt. Palomar Hale 200" telescope, providing characterization of these objects.

New, model-derived parameters (discussed in Chapter 3) of white dwarfs (WDs), are important additions to known WDs in the Galaxy. Modeling and analysis of spectroscopic observations of WDs provide atmospheric composition and estimates of effective temperature and surface gravity. Effective temperature and surface gravity are the fundamental parameters which characterize white dwarfs. Specific temperature ranges,
depending on spectral type, correspond to a regime where WDs are observed to pulsate. Pulsating WDs are of interest because asteroseismology can be used to study the interiors of white dwarfs, as discussed further in §3.1. Characterizing WDs is crucial to understanding how 95% of stars end their lives, and each WD we study increases our knowledge of this critical final stage of stellar evolution. We discuss model fitting, characterization, and preliminary parameters of our sample of 10 WDs in Chapter 3; one of our WDs is predicted to be a pulsator. An introduction to WDs, their characteristics, and evolution is discussed in §1.2.

V523 Lyr is a cataclysmic variable (CV) and is thought to be a specific subtype of CV, known as an SU UMa type, which will be discussed in detail in §1.3. Cataclysmic variables are a type of semi-detached binary system, which undergoes mass transfer via an accretion disk and produces quasi-periodic outbursts. An outburst is observed as an increase in brightness lasting several days. Studying V523 Lyr in depth, and over a long timeline, allows us to learn about the fundamental parameters of the system, outburst structure, and accretion mechanisms. Our analysis is used to confirm the nature of V523 Lyr and to constrain the orbital and physical parameters of this specific system. V523 Lyr exhibits outbursts lasting \( \sim 9 \) days and occurring every \( \sim 25 \) days. The unprecedented \textit{Kepler} photometric datasets together with Palomar spectroscopy allow for detailed study of the WDs and the CV, V523 Lyr.

White dwarfs and cataclysmic variables will be introduced in §1.2 and §1.3, respectively. \textit{Kepler} and Palomar observations and data reduction will be discussed in Chapter 2. In Chapter 3, we discuss the WD models, fitting for our WDs, and the extracted parameters and characterization for each of our 10 WDs. V523 Lyr is characterized using both photometric and spectroscopic observations to determine outburst structure and parameters of the system in Chapter 4. Finally, a summary of our results will be laid out in Chapter 5.
1.2 White Dwarfs

A white dwarf is the last stage of stellar evolution when the outer envelope of an evolving star has been expelled and only a dense core remains. White dwarf progenitors are single stars which had main sequence masses \( \lesssim 8M_\odot \), which corresponds to about 95% of all stars. Stars with main sequence masses greater than \( 8M_\odot \) are short-lived and usually end their lives as neutron stars or black holes. Nearly all white dwarf masses lie within a narrow range of 0.42\( M_\odot \) to 0.70\( M_\odot \) (Carroll & Ostlie, 2007), centered around 0.59\( M_\odot \) (Fontaine et al., 2001), with radii of order \( 10^6 \) m for most WDs (Carroll & Ostlie, 2007).

Physical parameters of WDs can be calculated by general stellar physics equations and determined by observed properties. All stars, including WDs, can be approximated to emit their radiation as a blackbody. A blackbody is an object which absorbs all incident light energy and reemits that light in a characteristic smooth and continuous spectrum that peaks at a specific wavelength. The peak wavelength is dependent on the temperature of the body, and determined by Wien’s displacement law,

\[
\lambda_{\text{max}} = \frac{0.002897755 \text{ m K}}{T},
\]

where \( T \) is the temperature of the body in Kelvin and \( \lambda_{\text{max}} \) is the wavelength in meters where the intensity of the radiating body is at its maximum. From spectral observations, we know that WDs do not produce smooth spectra, but instead show absorption lines, however the overall shape of the full electromagnetic spectrum loosely matches the shape of a blackbody spectrum (see Fig. 1.1). The effective temperature of a white dwarf’s atmosphere corresponds to a \( T_{\text{eff}} \) of a blackbody with the same flux, which is related to the luminosity of the WD by the Stefan-Boltzmann equation,

\[
L = 4\pi R^2\sigma T_{\text{eff}}^4,
\]

where \( L \) is the luminosity of the WD, \( R \) is the radius, \( \sigma \) is the Stefan-Boltzmann constant, and \( T_{\text{eff}} \) is the effective temperature. Effective temperatures of WDs range from \( \sim 4000 \) K up to 150,000 K, with the majority of WDs in the range between 6000 K and 50,000 K. Because of their small radii, WDs are therefore not very luminous, with luminosities ranging from about \( 10^{-4}L_\odot \) to \( 1.0L_\odot \).
A white dwarf is extremely compact with about half the mass of the sun compressed into the volume of an Earth-sized planet. In white dwarfs, electrons, which are fermions, a quantum mechanical classification of particles with spin $\pm \frac{1}{2}$, are degenerate. Each electron has a restrictive volume that it occupies, described by the quantum volume, $V_Q = \left(\frac{\hbar}{\sqrt{2\pi mkT}}\right)^3$, where $\hbar$ is Planck’s constant, $m$ is the mass of the degenerate particle, $k$ is Boltzmann’s constant, and $T$ is the temperature of the degenerate material (Schroeder, 2000). This quantum volume acts like a cube of space around the electron, which cannot be squished in any way. Degeneracy occurs in the core of a WD, where the temperature is so high the atoms are ionized and the electrons are free to move about, and are not bound to the atomic nuclei. The electrons become degenerate when the volume they are occupying is equal to the volume of all the quantum volumes of each electron added together. The quantum volumes cannot cross or combine in any way because the wave functions of the electrons cannot interfere with each other; electrons are fermions and cannot occupy the same space.

White dwarfs are stable at masses below $1.44M_\odot$, where the resulting electron degeneracy pressure pushing radially outward is balanced by gravity pulling radially inward. The $1.44M_\odot$ upper limit for a WD mass is known as the Chandrasekhar limit, which white dwarfs cannot exceed. If a WD exceeds the Chandrasekhar limit, gravity
wins out over electron degeneracy pressure and the core collapses. This collapse produces an increase in temperature, which causes fusion to begin again, and produces a thermonuclear runaway. The resulting thermonuclear explosion produces what is known as a Type Ia supernova. Theory suggests this process usually occurs in a binary system where the WD is accreting material from a companion\(^1\).

Diffusion occurs due to the high gravity of WDs, leaving the lightest elements, like hydrogen and helium, in the atmosphere, whereas the metals sink towards the core. However, throughout stellar evolution from the main sequence to the WD stage, dredge-up can occur, which effectively mixes elements throughout the star. Three different types of cores exist in WDs: helium (He), oxygen-neon-magnesium (ONeMg), and carbon-oxygen (CO). Helium cores are produced from progenitors with initial masses less than 1.0M\(_\odot\). These progenitors experience efficient mass loss, which causes the stellar evolution process to halt before the He flash phase can begin (Harpaz et al., 1987). The resultant WD mass is \(~0.5\)M\(_\odot\), which is lower than the mass required for degenerate helium ignition, so helium remains as the main core constituent (Mazzitelli, 1989). The second type of WD core is composed of oxygen, neon and magnesium, and results from initial WD progenitor masses near 8M\(_\odot\). High initial mass causes carbon ignition, which removes the core degeneracy. After carbon ignition, there is an “impulsive, but not disruptive carbon burning” phase, which produces a \(~1.2\)M\(_\odot\) ONeMg white dwarf core. The final core is composed of carbon and oxygen and is the most common WD core composition. Finally, most WD progenitors are of average mass and follow the usual path of stellar evolution, involving helium burning, which produces carbon and oxygen (D’Antona & Mazzitelli, 1990). After helium burning and asymptotic giant branch thermal pulses occur, CO white dwarf progenitors undergo possible mass loss or envelope ejection (Iben & Renzini, 1983). Another evolutionary possibility is that the

\(^1\)hubblesite.org/hubble_discoveries/dark_energy/de-type_ia supernovae.php
CO white dwarf progenitor goes through a second dredge-up stage after helium burning (Mazzitelli, 1989a).

Spectral observations of our WDs provide the means to determine their atmospheric composition. White dwarf spectra exhibit various atomic and molecular features, depending on the evolution of the progenitor star. Spectral classifications of WDs are made first on the general basis of hydrogen or helium dominated spectral features. There are two main classes of WD spectra, DA, which have hydrogen dominated atmospheres, and non-DA, which do not have hydrogen dominated atmospheres. The non-DAs encompass several WD spectral types: DO, DB, DQ, DZ, DC, and magnetic. The D stands for degenerate and the second letter represents the spectral type of the WD based on the elemental or molecular lines observed in the spectrum (see Table 1.1). DA WDs make up 75-80% of all known WDs with $T_{\text{eff}} > 10^4$ K (Sion, 1986). The WDs discussed in this thesis are all spectral type DA, however the other spectral types are summarized briefly in Table 1.1.

**Table 1.1:** Reproduced table of WD spectral type characteristics from Sion (1986) with additions from Oswalt (2013).

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Characteristics</th>
<th>$T_{\text{eff}}$(K) Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>DA</td>
<td>Only Balmer lines; no He I or metals present</td>
<td>6000 to 90,000</td>
</tr>
<tr>
<td>DB</td>
<td>He I lines; no H or metals present</td>
<td>12,000 to 30,000</td>
</tr>
<tr>
<td>DC</td>
<td>Continuous spectrum, no lines deeper than 5% in any part of the electromagnetic spectrum</td>
<td>$&lt; 10,000$</td>
</tr>
<tr>
<td>DO</td>
<td>He II strong; He I or H present</td>
<td>$45,000$ to $\gtrsim 10^5$</td>
</tr>
<tr>
<td>DZ</td>
<td>Metal lines only; no H or He</td>
<td>$&lt; 5500$?</td>
</tr>
<tr>
<td>DQ</td>
<td>Carbon features, either atomic or molecular, in any part of the electromagnetic spectrum</td>
<td>6000 to 12,000</td>
</tr>
<tr>
<td>Magnetic</td>
<td>$1 \lesssim B \lesssim 500$MG</td>
<td>4000 to 150,000</td>
</tr>
</tbody>
</table>

The high gravity of WDs produces pressure-broadened spectral absorption lines. Pressure broadening of spectral lines occurs when atoms in WD atmospheres collide or have frequent close encounters with one another. These collisions or encounters cause small perturbations of the electric fields of the atoms. The electric field perturbations cause the observed spectral line profile to resemble that of simple harmonic damping
of an electric charge; this profile is known as a Lorentz profile. The average time between collisions or encounters determines the specific shape of the profile observed in WD spectra (Carroll & Ostlie, 2007). In DA WD spectra, the hydrogen Balmer series absorption lines are observed as pressure-broadened line profiles. Pressure broadening dominates the shape of the Balmer series lines over the effects of natural and Doppler broadening. The shape of the Balmer line profiles are similar throughout our DA sample, but vary slightly based on temperature and gravity; examples can be seen in Chapter 3.

The hydrogen Balmer series encompasses transitions \( n > 2 \leftrightarrow n = 2 \), where \( n \), the principal quantum number, determines the quantized energy level of the electron making the transition. The Balmer series includes H\( \alpha \), H\( \beta \), H\( \gamma \), and H\( \delta \) as the most prominent lines, and the series occurs in the visible wavelengths, specifically from 3646.0Å to 6562.81Å. Transitions for some of the hydrogen Balmer absorption lines are displayed in Table 1.2. Specifically for the Balmer lines, there is a simple equation which dictates the wavelengths at which these transitions are observed at: \( \frac{1}{\lambda} = R_H \left( \frac{1}{4} - \frac{1}{n^2} \right) \), where \( R_H = 1.097 \times 10^7 \text{ m}^{-1} \) is the Rydberg constant, \( \lambda \) is the wavelength of emission or absorption, and \( n \) is the energy level. The Balmer lines are extremely apparent in DA WDs because hydrogen is abundant in their atmospheres and the temperatures are hot enough for electrons to populate the \( n = 2 \) level needed for these specific transitions, but not hot enough to ionize the hydrogen atoms. Spectral lines from other elements, such as metals, are mostly non-existent in observed spectra because they are not present in DA WD atmospheres. Metals diffuse to the core of DA WDs during differentiation and are not visible in optical spectra through the white dwarf’s thin atmosphere.
Table 1.2: Hydrogen Balmer series transitions for absorption lines used in modeling WDs, adapted from Carroll & Ostlie (2007).

<table>
<thead>
<tr>
<th>Spectral Line</th>
<th>n_{start}</th>
<th>n_{end}</th>
<th>Rest Wavelength Å</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>2</td>
<td>3</td>
<td>6562.81</td>
</tr>
<tr>
<td>Hβ</td>
<td>2</td>
<td>4</td>
<td>4861.34</td>
</tr>
<tr>
<td>Hγ</td>
<td>2</td>
<td>5</td>
<td>4340.48</td>
</tr>
<tr>
<td>Hδ</td>
<td>2</td>
<td>6</td>
<td>4101.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H_{limit}</td>
<td>2</td>
<td>∞</td>
<td>3646.0</td>
</tr>
</tbody>
</table>

1.3 Cataclysmic Variables

Two gravitationally bound stars which rotate around a common center of mass are known as a binary system. Binary stars can be widely separated, or extremely close together, and can involve any type or size of stars. Cataclysmic variables are a type of semi-detached binary star system which consists of a white dwarf primary and usually a low-mass main sequence secondary. The two stars are close enough together that the secondary can transfer matter to the white dwarf via an accretion disk, but not so close together to have a common envelope. Accretion physics will be discussed in detail in §4.1.

Cataclysmic variables are classified into categories based on their frequency and magnitude of outburst. Five types of CVs exist: classical novae, dwarf novae, nova-like variables, recurrent novae, and magnetic CVs (see Table 1.3). Classical novae (CNe) only display a single recorded outburst in their observation history, however theories suggest there may be previously unrecorded outbursts (e.g., Shara et al. 2012). Dwarf novae (DNe) have semi-periodic outbursts with peak brightness about ten times that at quiescence (Barclay et al., 2012). However, some DNe known as tremendous outburst amplitude dwarf novae (TOADs), have been observed to have an increase in brightness as much as 10 magnitudes from quiescence to outburst (Howell et al., 1995). Nova-like (NL) variables have a constant, heightened mean luminosity (Wood et al., 2011), as if
they are always in a brightness high state; NLs can be thought of as “non-eruptive” CVs (Warner, 1995). Recurrent novae (RNe) appear similar to CNe, with large amplitude outbursts, but they have been seen to exhibit more than one outburst, albeit separated by decades or more in time. RNe also consist of a fundamentally different type of semi-detached system, usually having long orbital periods and giant or supergiant secondaries (Warner, 1995). Magnetic CVs house WDs with strong magnetic fields, which disrupts disk accretion onto the WD and redirects material to accrete at the magnetic poles (Warner, 1995). V523 Lyr was confirmed by Howell et al. (2013) to be a dwarf nova (DN), so this thesis focuses on DNe from this point forward.

Table 1.3: Summary table of CV types.

<table>
<thead>
<tr>
<th>CV Type</th>
<th>Outburst Characteristics</th>
<th>Subclasses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classical Novae</td>
<td>single recorded outburst</td>
<td>none</td>
</tr>
<tr>
<td>Dwarf Novae</td>
<td>10X peak brightness increase from quiescence</td>
<td>SU UMa, Z Cam, U Gem</td>
</tr>
<tr>
<td>Nova-like</td>
<td>mean constant luminosity, non-eruptive CVs</td>
<td>UX UMa, RW Tri, SW Sex</td>
</tr>
<tr>
<td>Recurrent Novae</td>
<td>large amplitude outbursts with long periods</td>
<td>T Pyx, U Sco, T CrB</td>
</tr>
<tr>
<td>Magnetic CVs</td>
<td>can be classified in any of the above</td>
<td>polars, intermediate polars</td>
</tr>
</tbody>
</table>

DNe quasi-periodic outbursts arise from thermal instabilities which occur in the accretion disk. The dwarf nova class is further broken down into subclasses, SU UMa, Z Cam and U Gem systems, which are named for the first system which was discovered to show a specific type of deviant behavior. SU UMa systems exhibit superoutbursts as well as normal outbursts. The Z Cam subclass, after initial outburst, is characterized by a maintained brightness at about a magnitude below peak. These outbursts can sometimes halt for tens of days, or even several years. U Gem systems encompass all other DNe not included in either the SU UMa or Z Cam subclasses (Warner, 1995). Original classification of V523 Lyr included NL (UX UMa) or DN (Z Cam) by Kaluzny et al. (1997) and NL (VY Scl) or DN (Z Cam) by Mochejska et al. (2003). V523 Lyr, the CV of interest in this study, was suggested to be an SU UMa type dwarf nova using early Kepler observations (Howell et al., 2013); we now focus on the SU UMa subclass.
Superoutbursts occur during a regular outburst, but the increase in brightness is several magnitudes above a typical peak outburst brightness. These superoutbursts are caused by an increase in mass accretion onto the white dwarf from tidal dissipation. The proposed theory for this mechanism is that of Osaki (1989), which states that the accretion disk starts out with a low mass and an outer radius smaller than that of the 3:2 resonance. A 3:2 spin-orbit resonance occurs when the spinning star rotates three times in the same amount of time taken by the orbiting mass to go around the star twice. In the case of an accretion disk around a WD, the resonance is for material at the outer edge of the accretion disk. During a normal outburst, the disk expands slightly, but does not yet extend to the 3:2 resonance. Subsequent outbursts continue to expand the disk edge until it reaches beyond the resonance. The disk is now in a high viscosity state which is maintained by strong tidal dissipation at the edges of the now larger disk, causing angular momentum to now be lost at a great extent. The loss of angular momentum causes mass to move inward towards smaller radii and eventually accrete onto the WD, extending a normal outburst into a superoutburst (Warner, 1995).

Another phenomenon which occurs in SU UMa systems are superhumps. Superhumps are periodic episodes during a superoutburst with periods slightly longer than the orbital period of the binary system (Still et al., 2010). Neither superoutbursts or superhumps occur in the *Kepler* light curve of V523 Lyr, therefore V523 Lyr is not confirmed as an SU UMa type cataclysmic variable; details are discussed in Chapter 4.
Chapter 2

Observations and Data Reduction

Spectroscopic data of the WDs and V523 Lyr were obtained from the Mt. Palomar Hale 200" telescope over several nights in the summer of 2013. Photometric data was obtained from the Kepler space telescope over several months during its operational years from 2009 to 2013. Spectroscopic and photometric data were not obtained simultaneously. In the following sections, observational details and reduction processes of both the spectroscopic and photometric data are discussed.

2.1 Spectroscopic Observations

Optical, ground-based spectroscopic observations were obtained from the Palomar 200" (5.1-meter) Hale Telescope. The Hale telescope is located on Palomar Mountain in Southern California, where observations were taken over several observing runs from July 2013 through August 2013. Spectroscopic observations were conducted based on a program to discover hot WDs in the Kepler field, in order to use them as photometric calibrators. Target objects were selected in the Kepler field based on a UBV survey conducted by Everett et al. (2012) to find very blue objects, colors near $B - V = 0$
and $U - B = -0.8$ or bluer, on a $B - V$ versus $U - B$ color-color diagram. Blue $UBV$ survey objects were cross-correlated with high proper motion objects (catalogue from Sébastien Lépine, priv. comm.), which yielded several tens of WD candidates. High proper motion indicates the objects are relatively close to us, within our local neighborhood. The Hale 200” was used for ground-based, follow-up spectroscopy to complement Kepler photometry of both the WDs and the CV, V523 Lyr.

### 2.1.1 Palomar Instruments and Observations

A spectrograph, in its simplest form, is composed of a diffraction grating, a charge coupled device (CCD), and a camera. The CCD is a detector, which is used in conjunction with the camera to capture the image of the spectrum. Stellar light enters the spectrograph and goes through a diffraction grating. A diffraction grating is essentially a piece of material with hundreds of thin, equally spaced slits cut across it. When light hits the grating, it diffracts into several orders and splits the light which creates a spectrum. The CCD is placed at a point which usually captures the first or second order of diffracted light, as these are the orders with the highest power, besides the zeroth order (where diffraction does not occur). High resolution spectroscopic observations of faint objects usually require long exposure times because the diffracted stellar light is smeared out across the detector, effectively reducing its power. CCDs have inherent noise which is introduced into the data from the conversion of photons to electrons when producing a digital image. This noise is called read noise and is the root-mean-square (RMS) of all the possible causes of noise introduced into the detector from sources inherent to CCDs. Read noise limits how much signal to noise the camera can obtain and can be mitigated using standard reduction techniques (discussed below), or combining multiple images\(^1\).

\[^1\text{qsimaging.com/ccd_noise.html}\]
The Double Beam Spectrograph (DBSP) on the Hale 200" was used for our observations. The DBSP has two channels: “red” with a full wavelength range of 4700Å to 11,000Å, and “blue” with a full wavelength range of ~3000Å to 7000Å, both of which are used in this thesis. A D55 dichroic splits the incident light into the red and blue channels at 5500Å. A 1200 lines/mm grating was used for both channels, and corresponds to a dispersion of 26 and 36 Å/mm in the red and blue channels, respectively, constraining our wavelength ranges to 3500Å to 5000Å in the blue channel and 5500Å to 7500Å in the red channel. The CCD for the DBSP is 2098 × 4096 pixels in size, which corresponds to 31.47 × 61.44 mm. The blue channel has a scale of 0.389"/pixel and the red channel has a scale of 0.293"/pixel. Resolving power for the red channel is between 4000 and 5000 and resolving power for the blue channel between is 2500 and 3500, for our wavelength ranges. The blue channel grating is blazed for peak efficiency at 5000Å and the red channel grating is blazed for peak efficiency at 7100Å. Blazed gratings allow the reflection or transmission of the spectrum to be mostly concentrated into a higher order. At order n = 0, the light is not dispersed, but at higher orders, n = 1, 2, et al., a spectrum is produced through the dispersion of incident light. An example of a blazed grating is shown in a simplified schematic in Figure 2.1. Blazed gratings are more efficient than traditional gratings because blazed gratings force more power into the higher orders of diffraction.

The slit length of the spectrograph is 128" with widths ranging from 1" to 10". On a given observing night, the slit width is determined depending on observing conditions and is usually set to a value experimentally equal to that of the seeing. Seeing is a measure of how calm the atmosphere is for observing and also depends on the altitude and time of observation. Bad seeing causes images to not be as sharp or clear, and
is caused by fluctuations in the temperature and density of the Earth’s atmosphere. Better seeing allows for a smaller slit width, which provides better spatial resolution and in turn produces clear and distinct spectral features. On a good observing night, the seeing is \( \sim 1'' \); the slit width is set to 1'' for our observations. An object is also best observed when it is as close to the zenith as possible. When observing an object close to the zenith, there is less atmosphere for the light of the object to pass through, so it is less attenuated. The measurement of attenuation due to the amount of atmosphere we are looking through is dependent on the altitude of the object on the sky and is known as the airmass\(^5\).

The Hale 200'' is supervised by an on-site telescope operator. Telescope operations are now mostly automated and all observations can be completed from a warm room within the telescope dome. The observer chooses targets from a previously selected list of objects, uploads them to the operator, and the operator slews the telescope to the target. The telescope operator centers the object with confirmation from the observer. Observers use finder charts to see the field of view and make sure the target object is centered on the slit. The exposures are conducted by the observer on an interface

\(^5\)spiff.rit.edu/classes/phys445/lectures/atmos/atmos.html
which has independent controls for the red and blue channels of the DBSP. Red and blue channel observations can be conducted simultaneously, but each exposure must be independently executed. After each exposure is completed, the raw data is immediately available to view. We quickly viewed the raw spectrum to make sure the signal to noise is good, to ensure the correct object was obtained, and to determine if another exposure needs to be completed.

Calibrations also need to be obtained and can be completed at the beginning, the end, or throughout the night. Calibrations for spectral observations include obtaining zeros, flats, arc spectra, and flux calibrators. Zeros are zero second observations completed in order to assess any imperfections on the detector. Flats are used to correct any pixel to pixel variations across the detector. Flats can be obtained in a number of ways, but the most common are lamp flats and sky flats. To obtain a lamp flat, an incandescent lamp is shone into the telescope, or the telescope is pointed at a flat piece of wall illuminated with the lamp. An exposure is taken of the lamp, which presents an image of the imperfections of the camera. Sky flats are obtained by pointing the telescope at the sky at twilight and the same basic principle is accomplished. Arc spectra are obtained by taking an exposure of a lamp of known elements, helium-neon-argon (HeNeAr) for example. Rest wavelengths of He, Ne, and Ar are well known and can be identified in the arc spectrum. These lines are then used to wavelength calibrate the observed stellar spectra. Flux calibrators are standard stars which have known fluxes at various wavelengths and can be used to calibrate the flux of target objects. Table 2.1 shows the observation information for our sample; V523 Lyr magnitudes were obtained from Downes et al. (2001).
Table 2.1: Table of spectroscopic observations of WDs and V523 Lyr.

<table>
<thead>
<tr>
<th>Object Name</th>
<th>Obs Date</th>
<th>V mag</th>
<th># of Exposures per channel</th>
<th>Exp Time s</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMI18450+4800</td>
<td>10-08-2013</td>
<td>18.7</td>
<td>2</td>
<td>900</td>
<td>red/blue</td>
</tr>
<tr>
<td>PMI18486+4811</td>
<td>10-08-2013</td>
<td>18.5</td>
<td>2</td>
<td>900</td>
<td>red/blue</td>
</tr>
<tr>
<td>PMI18553+4755</td>
<td>09-08-2013</td>
<td>18.8</td>
<td>2</td>
<td>900</td>
<td>red/blue</td>
</tr>
<tr>
<td>PMI19002+3922</td>
<td>09-08-2013</td>
<td>15.7</td>
<td>1</td>
<td>900</td>
<td>red/blue</td>
</tr>
<tr>
<td>PMI19085+4338</td>
<td>11-08-2013</td>
<td>18.1</td>
<td>2</td>
<td>600</td>
<td>red/blue</td>
</tr>
<tr>
<td>PMI19141+4936</td>
<td>11-08-2013</td>
<td>16.7</td>
<td>2</td>
<td>600</td>
<td>red/blue</td>
</tr>
<tr>
<td>PMI19173+4452</td>
<td>11-08-2013</td>
<td>15.7</td>
<td>2</td>
<td>600</td>
<td>red/blue</td>
</tr>
<tr>
<td>PMI19245+3734</td>
<td>11-08-2013</td>
<td>18.2</td>
<td>2</td>
<td>900</td>
<td>red/blue</td>
</tr>
<tr>
<td>PMI19409+4240</td>
<td>09-08-2013</td>
<td>16.5</td>
<td>1</td>
<td>600</td>
<td>red/blue</td>
</tr>
<tr>
<td>V523 Lyr</td>
<td>01-07-2013</td>
<td>17.7 - 20.2</td>
<td>5</td>
<td>1200</td>
<td>red/blue</td>
</tr>
<tr>
<td>V523 Lyr</td>
<td>02-07-2013</td>
<td>17.7 - 20.2</td>
<td>7</td>
<td>1200</td>
<td>red/blue</td>
</tr>
</tbody>
</table>

### 2.1.2 Palomar Data Reduction

Spectra were reduced using the Image Reduction and Analysis Facility (IRAF) software. Preliminary analysis of the observed spectra was performed using the SPLOT task in the ONEDSPEC package. Using pre-programed IRAF scripts, each spectrum was reduced using the APALL task for extracting optical one-dimensional spectra. APALL includes several tasks in one routine, which can also be executed separately. These routines are as follows: APFIND, APEDIT, BACKGROUND, APTRACE, and then the extracted spectrum can be reviewed. APFIND allows the aperture, or width of the extraction, to be set automatically or manually. The spectrum itself only appears on a small sliver of the full image recorded on the CCD, which is related to the slit width and length. APEDIT was then used to edit the width of the aperture to be extracted. The aperture was used to determine where to extract the spectrum and how many pixels across to sum for the best signal. The background, or continuum, was fit using the BACKGROUND task, which determined the noise level of the surrounding sky. APTRACE was executed to determine the shape of the spectrum and how it evolved across the CCD. When the diffracted light falls onto the CCD to create a spectral image, there is a small angle offset, which causes the spectrum to not fall exactly in the center of, or in a straight line across, the image. Therefore, when a spectrum is extracted, it does not exactly follow a single row.
or column of pixels; this is where APTRACE is used. APTRACE traced the path of the
spectrum across the image using a low order polynomial in order to extract the best
spectrum possible.

Once the spectra were extracted with a proper aperture, they were then sky sub-
tracted to remove night sky lines, which naturally occur in the atmosphere when observ-
ing from the ground. The spectra were then wavelength calibrated with IDENTIFY, using
a HeNeAr arc spectrum for the blue channel and a FeAr (Iron-Argon) arc spectrum for
the red channel. Wavelength calibration was completed by identifying known spectral
lines in the calibration spectrum. These lines were used to fit the wavelength scale of the
 calibration spectrum, then this wavelength solution was applied to the observed spectra
using DISPCOR. Once the wavelength solution was applied, the flux was calibrated using
known spectrophotometric standard stars by the CALIBRATE task. Standard stars have
known magnitudes at specific wavelength ranges, and were used to calibrate the flux of
our observed spectra to the observed standard star’s flux. The spectral reduction was
complete at this stage and the data was then analyzed (see §3.2 & 4.4).

2.2 Photometric Observations

Photometric observations were obtained by the Kepler 0.95m space telescope, shown in
Figure 2.2\textsuperscript{6}, which has a bandpass of 4300-8900\textsuperscript{7}. Initial Kepler targets were observed
based on the Kepler Input Catalog (KIC), a catalogue comprised of a 16 million star
survey of the field to learn about objects which might be of interest (Brown et al., 2011).

Kepler observed \sim 150,000 stars of these 16 million, generally the brightest objects, as
well as additional objects during guest observer programs. Any object observed, or

\textsuperscript{6}www.nasa.gov/sites/default/files/images/707893main_Photometer_sc_labels_horiz_full.jpg
\textsuperscript{7}http://kepler.nasa.gov/
accepted proposed objects, have KIC numbers for the sake of cataloging and organizing the data. The observed KIC objects have pipeline-reduced light curves readily available, but other field objects, which were not directly, or indirectly observed, do not have light curves available. Five of our WDs do not have light curves available through the pipeline, or raw data files (discussed below).

![Schematic of the Kepler 0.95m space telescope.](http://kepler.nasa.gov/images/MilkyWay-Kepler-cRoberts-1-full.png)

**Figure 2.2:** Schematic of the *Kepler* 0.95m space telescope.

### 2.2.1 *Kepler* Observations

*Kepler* observed a 115 square-degree field of view in the Cygnus constellation almost non-stop, obtaining unprecedented photometric coverage of this field from 2009-2013. At that time, the second reaction wheel failed and the mission was reconfigured for *K2*. *K2* stares at several fields in the ecliptic for \(~80\) days each, with the same photometric precision and intention as the original *Kepler* mission. Figure 2.3\(^8\) displays *Kepler’s* field of view overlaid on an image of the Milky Way. Discovering and confirming planets via transits were the main objectives of *Kepler*, but its photometric precision and depth, down to 21 *Kepler* magnitudes, is also extremely beneficial for astronomical studies of variable systems. Astronomical events, flares or outbursts for example, can be easily

\(^{8}\)kepler.nasa.gov/images/MilkyWay-Kepler-cRoberts-1-full.png
detected by *Kepler* because the outbursts produce large variations in brightness, in comparison to an $\sim 1\%$ dip in brightness for Jupiter-sized planet transits. *Kepler* has two modes of observation, long cadence (LC; 30 minute exposures) and short cadence (SC; 1 minute exposures), both of which are used in this thesis. *Kepler* data is incremented in quarters, $\sim 90$ days, when the telescope would roll over and downlink data to Earth.

![Kepler Field overlaid on the Milky Way Galaxy.](image)

**Figure 2.3:** The *Kepler* field overlaid on the Milky Way Galaxy.

All *Kepler* data is archived, publicly available from the Mikulski Archive for Space Telescopes\(^9\) (MAST), and unrestricted as of 28 October 2012. Data can be downloaded in the form of pipeline-reduced light curves, target pixel files (TPFs), or full frame images (FFIs). Full-frame images, taken approximately once per month directly before the downlink of data to Earth, are 30 minute exposures of the entire field. TPFs are downloaded as postage stamps, and can be used to discover fortuitous background objects which have been imaged because of their close proximity to a target object. TPFs can also be used in order to re-extract and re-reduce the data instead of using the pipeline-reduced light curves; this is especially useful if a more in depth analysis is necessary, for example in crowded fields. This thesis used the TPFs to re-extract light curves of the CV, V523 Lyr, but used pipeline-reduced light curves for the 10

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\(^9\)archive.stsci.edu
white dwarfs. Normalized WD light curves were obtained through the NASA Exoplanet Archive\textsuperscript{10} (NEA). Simple aperture photometry (SAP) data was used for V523 Lyr and presearch data conditioning simple aperture photometry (PDCSAP\textsuperscript{11}) data was used for the white dwarfs.

Table 2.2: Table of WD photometric data.

<table>
<thead>
<tr>
<th>Name</th>
<th>KIC</th>
<th>\textit{Kepler}</th>
<th>Light Curve?</th>
<th>Mode</th>
<th>Quarters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>y/n</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PMI18450+4800</td>
<td>10709534</td>
<td>n</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PMI18486+4811</td>
<td>10777440</td>
<td>n</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PMI18553+4755</td>
<td>10649118</td>
<td>n</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PMI19002+3922</td>
<td>4242459</td>
<td>y</td>
<td>LC</td>
<td>1-17</td>
<td></td>
</tr>
<tr>
<td>PMI19002+3922</td>
<td>4242459</td>
<td>y</td>
<td>SC</td>
<td>6-13</td>
<td></td>
</tr>
<tr>
<td>PMI19085+4338</td>
<td>7879431</td>
<td>n</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PMI19141+4936</td>
<td>11604781</td>
<td>y</td>
<td>LC</td>
<td>3, 6, 7, 10, 11</td>
<td></td>
</tr>
<tr>
<td>PMI19141+4936</td>
<td>11604781</td>
<td>y</td>
<td>SC</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>PMI19173+4452</td>
<td>8682822</td>
<td>y</td>
<td>LC</td>
<td>1, 5-9</td>
<td></td>
</tr>
<tr>
<td>PMI19173+4452</td>
<td>8682822</td>
<td>y</td>
<td>SC</td>
<td>1, 5</td>
<td></td>
</tr>
<tr>
<td>PMI19179+4524</td>
<td>9082980</td>
<td>n</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PMI19245+3734</td>
<td>2158770</td>
<td>y</td>
<td>LC</td>
<td>6-9</td>
<td></td>
</tr>
<tr>
<td>PMI19409+4240</td>
<td>7129927</td>
<td>y</td>
<td>LC</td>
<td>3, 5, 6</td>
<td></td>
</tr>
<tr>
<td>PMI19409+4240</td>
<td>7129927</td>
<td>y</td>
<td>SC</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Tables 2.2 and 2.3 list the photometric observation information for all of the objects in this thesis. We note that V523 Lyr has a different KIC number associated with it for each quarter because V523 Lyr is in close proximity, on the sky, to a star cluster, NGC 6791. When \textit{Kepler} observes a cluster, or a very bright object, a custom aperture is defined, for example, for each object in the cluster. This causes each observation to have a new identification number for each quarter the cluster is observed. These are called custom aperture file (CAF) observations and all these observations have KIC numbers > 100,000,000\textsuperscript{12}. In order to ensure that all appropriate light curves were obtained for V523 Lyr, we searched for data for V523 Lyr within a radius up to 1.0’. The coordinates which are matched when searching the \textit{Kepler} archive are those for the center of the image, which in our case is not necessarily the center of V523 Lyr. There is a single

\begin{footnotesize}
\begin{itemize}
\item \textsuperscript{10}exoplanetarchive.ipac.caltech.edu
\item \textsuperscript{11}archive.stsci.edu/kepler/manuals/archive_manual.pdf
\item \textsuperscript{12}archive.stsci.edu/mast_faq.php?mission=KEPLER
\end{itemize}
\end{footnotesize}
KIC number associated with V523 Lyr, KIC 2438114, but this KIC number was only observed during quarters 6 to 9. However, V523 Lyr is located within the TPFs for the KIC numbers noted in Table 2.3. Light curve extraction details and clarification of the implications will be discussed in the next section.

Table 2.3: Table of photometric observations of V523 Lyr

<table>
<thead>
<tr>
<th>KIC</th>
<th>Start Date</th>
<th>End Date</th>
<th>Quarter</th>
<th>Cadence</th>
</tr>
</thead>
<tbody>
<tr>
<td>100002727</td>
<td>24-06-2010</td>
<td>22-09-2010</td>
<td>6</td>
<td>LC</td>
</tr>
<tr>
<td>100003069</td>
<td>23-09-2010</td>
<td>22-12-2010</td>
<td>7</td>
<td>LC</td>
</tr>
<tr>
<td>100003411</td>
<td>06-01-2011</td>
<td>14-03-2011</td>
<td>8</td>
<td>LC</td>
</tr>
<tr>
<td>100003514</td>
<td>23-03-2011</td>
<td>26-06-2011</td>
<td>9</td>
<td>LC</td>
</tr>
<tr>
<td>100003514</td>
<td>21-03-2011</td>
<td>26-04-2011</td>
<td>9</td>
<td>SC</td>
</tr>
<tr>
<td>100003517</td>
<td>27-04-2011</td>
<td>25-05-2011</td>
<td>9</td>
<td>SC</td>
</tr>
<tr>
<td>100003520</td>
<td>26-05-2011</td>
<td>26-06-2011</td>
<td>9</td>
<td>SC</td>
</tr>
<tr>
<td>100003562</td>
<td>27-06-2011</td>
<td>28-09-2011</td>
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<td>LC</td>
</tr>
<tr>
<td>100003608</td>
<td>29-09-2011</td>
<td>04-01-2011</td>
<td>11</td>
<td>LC</td>
</tr>
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<td>27-06-2012</td>
<td>13</td>
<td>LC</td>
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<td>30-04-2012</td>
<td>13</td>
<td>SC</td>
</tr>
<tr>
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<td>27-06-2012</td>
<td>13</td>
<td>SC</td>
</tr>
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<td>14</td>
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</tr>
<tr>
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<td>05-10-2012</td>
<td>11-01-2013</td>
<td>15</td>
<td>LC</td>
</tr>
<tr>
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<td>05-10-2012</td>
<td>05-11-2012</td>
<td>15</td>
<td>SC</td>
</tr>
<tr>
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<td>06-12-2012</td>
<td>15</td>
<td>SC</td>
</tr>
<tr>
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<td>07-12-2012</td>
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<td>15</td>
<td>SC</td>
</tr>
<tr>
<td>100004182</td>
<td>12-01-2013</td>
<td>08-04-2013</td>
<td>16</td>
<td>LC</td>
</tr>
</tbody>
</table>

2.2.2  *Kepler* Data Reduction

*Kepler* Guest Observer (GO) reduction and analysis PYRAF software, PyKE (Still & Barclay, 2012), is publicly available\(^\text{13}\) and was used for light curve reduction and analysis of the V523 Lyr light curves, as mentioned previously. Light curves, after initial analysis of the pipeline-reduced curves, were re-extracted and analyzed using several PyKE tasks: KEPPIXSERIES, KEPFIELD, KEMPASK, KEPUPLOAD, KEPRANGE, KEPOUTLIER, KEPCHOTREND, KEPARITH, KEPPCONNECT, KEPDRAW, and KEPIDETREND. A brief description of the function of each task is listed in Table 2.4.

\(^{13}\)keplerscience.arc.nasa.gov/
### Table 2.4: Summary of the function of each PyKE task used in this thesis.

<table>
<thead>
<tr>
<th>Task</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>keppixseries</td>
<td>produces a .png file displaying the raw light curve for each pixel</td>
</tr>
<tr>
<td>kepfield</td>
<td>identifies the location of KIC and non-KIC sources on the TPF</td>
</tr>
<tr>
<td>kepmask</td>
<td>creates a user-defined mask of pixels to be extracted to produce a light curve</td>
</tr>
<tr>
<td>kepextract</td>
<td>extracts a light curve using a user-defined mask from kepmask output</td>
</tr>
<tr>
<td>kepdraw</td>
<td>produces a .png file of a defined light curve</td>
</tr>
<tr>
<td>keprange</td>
<td>defines a range of times to use, or exclude, for other PyKE tasks</td>
</tr>
<tr>
<td>kepoutlier</td>
<td>finds and removes any data points which are 3σ above a fit of the data</td>
</tr>
<tr>
<td>kepcotrend</td>
<td>corrects the light curve flux for known variations during each quarter using cotrending basis vectors</td>
</tr>
<tr>
<td>kepdetrend</td>
<td>fits outlying data, usually caused by a gap in data, to the continuum</td>
</tr>
<tr>
<td>keparith</td>
<td>applies an arithmetic function to the data</td>
</tr>
<tr>
<td>kepconvert</td>
<td>converts fits light curve data to another format, ascii for example</td>
</tr>
</tbody>
</table>

TPFs were downloaded for each quarter of data for V523 Lyr and were analyzed individually. The TPFs contain several pixels surrounding the object of interest, which sometimes include other nearby objects. KEPPIXSERIES was executed to show the full aperture used to extract the pipeline-reduced light curve (shown in the top left of Figure 2.4). KEPFIELD was then executed to produce an image map of the pixel layout with the known sources within the TPF (shown in the top right of Fig. 2.4). In order to determine which pixels actually contained a light curve for V523 Lyr, a mask of each pixel was created using KEPMASK (see the bottom of Fig. 2.4), and then the light curve was extracted for each individual pixel, using KEPEXTRACT. IRAF scripts were used to automate the process of creating a mask and extracting each pixel’s light curve for each quarter of V523 Lyr. After the pixels were extracted, the light curves were viewed and examined using KEPDRAW to determine which pixels contained a light curve of V523 Lyr. These pixels were then identified in the TPF and KEPMASK, KEPEXTRACT, and KEPDRAW were executed, but this time for the selected pixels, which contained V523 Lyr. After the light curve was extracted, KEPOUTLIER was executed to remove data outliers caused by cosmic rays. KEPRANGE was then executed to select regions to be included or excluded for subsequent PyKE tasks. This task is used to preserve the outbursts in V523 Lyr and to constrain the ranges for the continuum for the normalization processes. KEPCOTREND was then used to apply cotrending basis vectors to the light
Figure 2.4: Top left: Example output of KEPPIXSERIES showing the raw light curve of each pixel. Greyed boxes show the aperture used for the pipeline-reduce light curves. Top right: Example output of KEPFIELD displaying all the known sources within this particular field. Green circles denote KIC sources, with larger circles corresponding to brighter objects, and red circles denote non-KIC sources. Bottom: Example of the GUI (graphical user interface) for KEMPRESS, where the green box represents the pixel which was chosen for the mask.

curve, which account for systematic errors in the data over each quarter. For some of the quarters, KEPDETREND was also necessary to account for systematic errors in data and to help correct the flux. Normalized flux of each light curve was conducted by dividing out the median value of each light curve using KEPARITH. This process was completed to get the data onto one scale for comparison from quarter to quarter. The final PyKE task used was KEPCONVERT, which was used to convert the fits data files for each light curve into ascii files, so the data could be displayed altogether and in a more aesthetically pleasing style. The full processed V523 Lyr light curve will be analyzed and displayed in Chapter 4.
The NEA houses pipeline-reduced light curves and tools, including normalization and period analysis, which were used for our WD light curves, as noted previously. The NEA periodogram tool computes the most likely period of a *Kepler* light curve using the Lomb-Scargle method. Several periods are calculated and the extracted periods can be used to phase the data. Phasing the data helps to determine if the period computed is accurate and true. The NEA period calculation tools are used in this thesis to determine periods for WD variability (discussed in Chapter 3) and to attempt to calculate an orbital period for V523 Lyr (discussed in §4.3).
Chapter 3

Modeling of DA White Dwarfs

3.1 White Dwarf Pulsations

Pulsations in stars occur in two main non-radial modes: p-modes and g-modes. The p-modes are produced by restorative pressure waves reacting to sound waves moving through the star, and are useful for studying the outer layers of a star. The g-modes are restorative gravity waves deep in the interior of a star driven by buoyancy in a star, and are useful for studying the core of a star. In WDs however, g-modes occur in the outer layers and p-modes occur in the interior due to how waves propagate throughout the star, which is the opposite from most stars, like the Sun (Hansen, Kawaler & Trimble, 2004). Pulsating WDs exhibit g-mode pulsations, which cause temperature variations on the surface due to the small changes in local radius. These temperature variations are observed in photometric data as small, periodic variations in brightness (Carroll & Ostlie, 2007). Pulsations in WDs usually have several periods of order minutes or hours, up to of order a day (Fontaine & Brassard, 2008). Using the period-mean density relationship, \( \Pi \approx \frac{1}{[\sigma(\rho)]^{1/2}} \approx \frac{0.04}{[\rho/\rho_\odot]^{1/2}} \), the typical mean density for a WD, \( \langle \rho \rangle = 1.41 \text{ g cm}^{-3} \), and \( \langle \rho_\odot \rangle \approx 10^6 \text{ g cm}^{-3} \), \( \Pi_p \lesssim 4 \text{s} \) (Hansen, Kawaler & Trimble, 2004). Pulsation
periods for p-modes, $\Pi_p$, are much too short for typical pulsation periods observed in pulsating DA white dwarfs; p-modes are not responsible for DA white dwarf pulsations. Asteroseismology is the study of the internal structure of stars using pulsation modes, and it can be used to study the internal structure of pulsating white dwarfs.

Pulsations occur in three different WD spectral types: DA, DB, and DO. DAVs, or ZZ Ceti stars, are pulsating WDs of the DA spectral class. These pulsators are found to occur around $T_{\text{eff}} \sim 12,000$ K, a temperature at which hydrogen is partially ionized (Montgomery et al., 2008). DBV is the designation for DB WDs which pulsate, found within the range $22,000$ K $< T_{\text{eff}} < 29,000$ K with an uncertainty of about $\pm 2000$ K (Beauchamp et al., 1999). Pulsating WDs of the DO spectral class are known as DOVs or PG1159 (GW Vir) pulsators. PG1159 pulsators are found to occur in a range of effective temperatures, from 75,000 K to 200,000 K (Kepler et al., 2014). Figure 3.1 displays an evolutionary track for a 13 Gyr old star (Marigo et al., 2008) with instability strips of DOV, DBV, and DAV overlaid (Winget & Kepler, 2008; Corsico & Althaus, 2006; Beauchamp et al., 1999; Gianninas et al., 2006; Castanheira et al., 2007).

Instability strips in WDs occur at temperatures where elements like hydrogen or helium are known to be partially ionized. In these partial ionization zones, two mechanisms are at work to produce the observed pulsations, the $\kappa$- and $\gamma$-mechanisms. The $\kappa$-mechanism, or opacity mechanism, occurs in the layer of the WD where, for example, hydrogen is partially ionized. In this layer, the work done on the gas to compress it causes further ionization and the layer absorbs heat during the compression stage. Compression causes an increase in both opacity, $\kappa$, and density, $\rho$. The layer then expands and releases heat, which causes ions to recombine with electrons and release energy. During expansion, the opacity and density in the partial ionization layer decrease. These processes continue in cycles, which are reinforced by the $\gamma$-mechanism, and together, cause the observed pulsations. The $\gamma$-mechanism is the tendency of heat to
flow into the partial ionization zone from the adjacent layers due to the smaller increase in temperature in the adjacent layers compared to the partial ionization layer (Carroll & Ostlie, 2007). Since the WDs in this thesis are spectral type DA white dwarfs, we discuss DAVs further below.

![Evolutionary diagram of a 13 Gyr old star with the instability strips over plotted on the evolutionary track.](image)

**Figure 3.1:** Evolutionary diagram of a 13 Gyr old star with the instability strips over plotted on the evolutionary track.

DA white dwarf pulsators were named after the first DA white dwarf which was found to show pulsations, ZZ Ceti, and are the best known and most common WD pulsators. Nitta et al. (2009) claims that the instability strip, where pulsations are found to occur, is a range dependent on temperature, mass, and atmospheric composition. The instability strip is located in the range $10,800 \, \text{K} < T_{\text{eff}} < 12,300 \, \text{K}$ (Bergeron et al., 2004; Mukadam et al., 2004) and is thought to have only a small dependence on mass (Castanheira et al., 2010). Determining the interior structure of pulsating WDs leads to determining their interior composition, which then allows us to identify the type of progenitor. Core composition is best estimated by combining observations of the change in pulsation period with evolutionary models of WDs (Winget & Kepler, 2008). Studies by Fontaine et al. (1982) and Greenstein (1982) claim that DA white dwarf pulsations
are actually a phase through which all DA white dwarfs evolve as they cool. If this is true, then studying the seismological properties of DA white dwarfs would provide constraints on the properties of all DA white dwarfs (Daou et al., 1990). From theoretical modeling, the blue edge of the instability strip is observed to be a sensitive function of WD mass and the characteristics of the hydrogen envelope, especially how effective convective mixing is in the hydrogen envelope (Winget & Fontaine, 1982). Studying the blue edge of the instability strip by determining effective temperatures of pulsating DA white dwarfs which fall near this edge, would therefore contribute to constraining the evolution of DA white dwarfs (Daou et al., 1990). The red edge of the instability strip is defined by the temperature at which convection begins to occur. Asteroseismology is not conducted in this thesis, however preliminary parameters of effective temperature and surface gravity are produced (discussed in next section) to determine if any of our 10 WDs are pulsators and can therefore be studied more in depth with asteroseismology.

### 3.2 Spectral Modeling

Our white dwarf spectra from the Hale telescope were modeled to determine their effective temperature and log g value, allowing candidate pulsators to be found. The acceleration due to gravity at the surface of the WD, $g = \frac{GM}{R^2}$, is measured in centimeters per second squared. Effective temperature and surface gravity are fundamental parameters of a white dwarf and measurements are possible from direct spectroscopic observations. These values are used to determine if the DA white dwarf is a pulsator. White dwarfs cool over time, so if the effective temperature of an observed WD is low, $\sim 6000$ K, it is older than a WD with an effective temperature of $\sim 30,000$ K, for example. This assumption comes from the idea that WDs are quite hot when they form and cool over time as they evolve. White dwarf cores composed of heavier elements cool faster than those composed of lighter elements (Winget & Kepler, 2008). Measurement
of the surface gravity of a WD provides us with an idea of how stratified the interior of the WD is and the possible core composition. However, the gravity only gives us part of the information we need to determine a WD’s structure, we need asteroseismology to probe the interior of a WD and determine its internal structure.

DA white dwarfs are the most common type of white dwarf, and the easiest to identify and model. The Balmer series absorption lines in WDs have a characteristic shape, which is easily recognizable. DA white dwarfs were identified and selected by eye during the preliminary analysis of all the Palomar spectra obtained from the original sample of our spectroscopic survey. Their spectra exhibit clean, gravity broadened absorption features of the hydrogen Balmer series, which can be clearly seen in the blue and red spectra, in the figures in sections 3.3.1 to 3.3.10.

DA white dwarf models were provided by Detlev Koester (priv. comm.); a discussion of the models and their usage can be found in Koester (2010). Koester (2010) produced models using four simplifying assumptions: homogenous, plane-parallel layers, hydrostatic equilibrium, radiative and convective equilibrium, and most importantly, local thermodynamic equilibrium. The plane-parallel approximation is used to make modeling stellar atmospheres less computationally intensive, as it assumes the pressure scale height, \( H = \frac{kT}{\mu g} \), where \( k \) is the Boltzmann constant, \( T \) is the temperature, \( \mu \) is the mean molecular weight of the atmospheric material, and \( g \) is the local gravitational acceleration, is much smaller than the radius of curvature of the star, \( R \). The pressure scale height is the distance to move up in the atmosphere for the pressure to decrease by 1/e (Carroll & Ostlie, 2007). Hydrostatic equilibrium is the balance between pressure outwards and gravity inwards, which keeps the star in balance (Carroll & Ostlie, 2007). Radiative and convective equilibrium in this context means that there is no generation or loss of energy within the atmospheric layers, but energy can still be transferred by all forms from the deep interior to the atmospheric layers. The effective temperature
is also assumed to be constant at all depths in the atmosphere (Koester, 2010). Local thermodynamic equilibrium means that locally, not across the whole star, there is no energy removed from or added to the radiation field (Carroll & Ostlie, 2007).

Initially, 189 models were used with temperatures ranging from 6000 K to 50,000 K and log g ranging from 7.00 to 9.00 dex. From 6000 K to 20,000 K, the grid spacing was ±1000 K and from 20,000 K to 50,000 K, the grid spacing was ±5000 K; surface gravity spacing was ±0.25 dex. This temperature range was used because most DA white dwarfs have effective temperatures within this range; only a few are known to have $T_{\text{eff}} > 50,000$ K. A best fit model was determined for each of our DA white dwarfs (discussed in detail below) and then a finer grid was used, which was focused around the initial temperature and gravity estimate. The finer grid was composed of 486 models and had grid spacing of ±250 K from 9000 K to 20,000 K and ±1000 K from 20,000 K to 30,000 K; log g spacing remained ±0.25 dex.

The models and observed spectra were normalized to the point closest to 4500 Å for the blue spectra and 7000 Å for the red spectra. We note that the model does not always extend to the very blue end of the observed spectrum; this is because the models are not accurate in this region. This portion of the observed spectrum has been removed from our figures for this reason. The models also do not reproduce the red wing of H$\beta$ well because the sensitivity is lower at the edges of the detector, causing a downturn in flux of the observed spectrum, which is not fully corrected in the reduction process. Therefore, the model fits by eye did not take into account the red wing fitting of the model of H$\beta$. A few bad sky subtractions and cosmic rays occur in the spectra; the corresponding data points were deleted cosmetically in order to show the true fit of the model to the observed spectrum. The models did not need to be convolved with the PSF of the observed spectra because the Balmer absorption features are much broader than the spectral resolution.
I wrote a series of programs in Python to compare the models and observed spectra visually and statistically. The original models contained less data points than the observed spectra, so the models were interpolated to fit the observed spectra in wavelength space. Mathematical calculations and graphical comparisons were completed in order to determine the best fit for each spectrum. First, a simple chi-square was calculated using the Python routine, `scipy.stats.chisquare()`. The chi-square function calculates the goodness of fit of the observed spectrum to the model spectrum. The residuals were also calculated between the model and the observed spectra. These residuals were then analyzed by eye in comparison plots where the best fit was determined (see §3.3.1 - 3.3.10). There were one to two observations of each object conducted on a given night; each spectrum was analyzed individually. These methods were used for the blue and red spectra separately. The blue and red best fit parameters were then compared to determine if they agreed with one another. A heavier weight was placed on the blue spectrum fit since they contain Hβ, Hγ, and Hδ, whereas the red spectrum only contains Hα. Each of the best fits, from the methods above, were then selected and the resulting parameters are discussed in the following sections.

### 3.3 Spectral and Photometric Analysis for DA White Dwarfs

The following explains the spectral and photometric analysis for each of the 10 identified DA white dwarfs in our sample. The statistical and graphical best fit methods discussed in the previous section were compared to determine parameters for each white dwarf. Qualitatively there are some intrinsic errors in determining the best fit by eye, but sometimes the eye is the best tool to identify the subtle differences between two statistically good fits. As seen from Table 2.2, half of the identified DA white dwarfs
have light curves in *Kepler*. Of these, only one WD shows small periodic variations and is discussed in §3.3.6. One white dwarf, PMI18450+4800 is predicted to be a pulsator from its determined parameters, but was not observed by *Kepler*. We therefore cannot determine if PMI18450+4800 shows periodic variations. Table 3.1 lists the best fit parameters for each DA white dwarf in our sample, obtained from modeling the blue spectrum of each white dwarf.

**Table 3.1**: Table of modeled DA white dwarf parameters derived from the blue spectra.

<table>
<thead>
<tr>
<th>Object</th>
<th>RA H:M:S.s</th>
<th>DEC D:M:S.s</th>
<th>$T_{\text{eff}}$ K</th>
<th>log g dex</th>
<th>Predicted Pulsator?</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMI18450+4800</td>
<td>18:45:05.63</td>
<td>+48:00:41.20</td>
<td>11750</td>
<td>8.25</td>
<td>possible</td>
</tr>
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<td>PMI18486+4811</td>
<td>18:48:37.94</td>
<td>+48:11:24.93</td>
<td>13500</td>
<td>8.00</td>
<td>no</td>
</tr>
<tr>
<td>PMI18555+4755</td>
<td>18:55:21.39</td>
<td>+47:55:44.94</td>
<td>20000</td>
<td>7.75</td>
<td>no</td>
</tr>
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<td>+39:22:32.90</td>
<td>18000</td>
<td>7.00</td>
<td>no</td>
</tr>
<tr>
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<td>19:08:34.01</td>
<td>+43:38:30.16</td>
<td>15000</td>
<td>7.75</td>
<td>no</td>
</tr>
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<td>+49:36:41.04</td>
<td>21000</td>
<td>7.00</td>
<td>see §3.3.6</td>
</tr>
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<td>+44:52:39.78</td>
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<td>8.25</td>
<td>no</td>
</tr>
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<td>13500</td>
<td>8.00</td>
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</tr>
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<td>+42:40:31.48</td>
<td>18750</td>
<td>7.25</td>
<td>no</td>
</tr>
</tbody>
</table>

### 3.3.1 PMI18450+4800 (KIC 10709534)

The modeled estimates for temperature and surface gravity place PMI18450+4800 in the instability strip. $T_{\text{eff}} = 11,750$ K and log g = 8.25 are the parameters determined from the analysis of the blue spectra of PMI18450+4800. The red spectrum parameters are statistically the same as the blue parameters, with $T_{\text{eff}} = 11,750$ K and log g = 7.00, maintaining PMI18450+4800’s status as a possible pulsator. Figures 3.2 and 3.3 show the blue and red spectra, respectively with the best model fits for each and residuals of the fit in the bottom panel. The blue spectrum model fits the line profiles of H$\beta$, H$\gamma$, and H$\delta$ well; the continuum around those lines also fit well. H$\alpha$ is modeled well, but the spectrum is quite noisy and the observed line profile is not deep or clean. The red
spectrum parameters are only used to help confirm and support the blue model fit, not to make an independent measurement.

Unfortunately there is no data available for PMI18450+4800 in the Kepler archive. We are therefore unable to confirm the pulsation nature of PMI18450+4800. PMI18450+4800, as well as other DA white dwarfs in our sample, have KIC numbers but were not observed before Kepler’s original mission ended. The archive was searched for nearby objects which may have included PMI18450+4800 (or others in our sample) within their apertures, but none were found.

PMI18450+4800 is labeled as a rotationally variable star in SIMBAD and only has a 2MASS designation. Therefore this object is a newly discovered and classified DA white dwarf, which is also a possible pulsator.

Figure 3.2: PMI18450+4800 blue spectrum with best fit model overlaid in red.
3.3.2 PMI18486+4811 (KIC 10777440)

The parameters derived from the spectral modeling of PMI18486+4811 do not place it within the instability strip. Analysis of the blue spectra yielded $T_{\text{eff}} = 13,500$ K and $\log g = 8.00$, whereas the red spectral analysis determined $T_{\text{eff}} = 14,000$ K and $\log g = 7.00$. These parameters are statistically in agreement; there is not a statistically significant difference between the best fit parameters of the red spectrum and the blue best fit parameters. Blue and red spectral parameters do not bring the effective temperature into the instability strip; PMI18486+4811 is not a pulsator.

For the blue spectra, the model fit well on the depth and wings of H$\gamma$ and H$\delta$. H$\beta$ was fit well in depth, but the blue wing slope was not fit well. The shape of the wings of H$\alpha$ are not well represented from the best model fit, but the line center and profile parameter values complement the blue modeled parameters. The continuum in the observed red spectrum has a different shape than the linear continuum of the model.
Observed spectra with overlaid best model fits are presented in Figures 3.4 and 3.5 for the blue and red spectra, respectively. No light curves were available for PMI18486+4811 for the reasons stated in §3.3.1, so PMI18486+4811 could not be verified as a non-pulsator.

PMI18486+4811 is not a known WD or a known 2MASS object. A search was conducted in SIMBAD and no object was found within 2′ of the RA and DEC of PMI18486+4811. Within 5′ of PMI18486+4811’s coordinates, three objects were found: KIC10843181, an IRAS source, and a Tycho source labeled as a star. KIC10843181 was checked to see if possibly PMI18486+4811 was close enough to be found within the aperture, but PMI18486+4811 was not within the TPF. PMI18486+4811 is a newly discovered and classified non-pulsating DA white dwarf in the *Kepler* field.

![Figure 3.4: PMI18486+4811 blue spectrum with best fit model overlaid in red.](image)
3.3.3 PMI18553+4755 (KIC 10649118)

Spectral analysis of the blue spectrum for PMI18553+4755 yielded $T_{\text{eff}} = 20,000$ K with log $g = 7.75$, setting it far above the instability strip. The modeled parameters for the red spectra support the hypothesis that PMI18553+4755 is not a pulsator and are in statistical agreement with the blue model parameters, providing $T_{\text{eff}} = 20,000$ K with log $g = 7.25$. Balmer profile fits of the model on the blue spectrum match the shape and depth very well, but there is a continuum dip between H$\delta$ and H$\gamma$, which does not match the shape of the model well. The H$\alpha$ line profile and red spectrum continuum are also fit well, considering only the general trend of the continuum. Model fits of the blue and red spectra of PMI18553+4755 can be seen in Figures 3.6 and 3.7, respectively. The red end of the red spectrum dips down and is an effect of the reduction of this high resolution spectrum and is not physical. PMI18553+4755 also did not have *Kepler* time series data, so the non-pulsation nature of this WD could not be confirmed.
Figure 3.6: PMI18553+4755 blue spectrum with best fit model overlaid in red.

Figure 3.7: PMI18553+4755 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line.
PMI18553+4755 is not found in SIMBAD using its central coordinates, but three sources were found within a 5’ radius. There are two Tycho sources, classified vaguely as stars, and a third Tycho object which is also named KIC10649021. Background sources within the KIC10649021 aperture were searched in order to find PMI18553+4755, but the object was not found in the TPF. PMI18553+4755 is a newly discovered and classified non-pulsating DA white dwarf.

3.3.4 PMI19002+3922 (KIC 4242459)

PMI19002+3922 is not a pulsator with model parameters from the blue spectral analysis of \( T_{\text{eff}} = 18,000 \) K with \( \log g = 7.00 \). An effective temperature of 18,000 K is too hot for this DA white dwarf to be considered a pulsator. Modeling of the red spectra statistically agrees with the blue, showing an effective temperature of 18,000 K and \( \log g = 7.75 \). PMI19002+3922’s observed blue spectra have a high signal to noise ratio and exhibit clean, deep Balmer lines. \( \text{H}\beta \), \( \text{H}\delta \) and \( \text{H}\gamma \) profiles are fit very well. The continuum has been fit well in most of the spectrum, except for a dip between \( \text{H}\gamma \) and \( \text{H}\delta \). The \( \text{H}\alpha \) profile is fit well in depth and shape through the wings, except for a dip in the blue wing, which causes the continuum to not fit well in this area. The blue and red observed spectra with overlaid model fits can be seen in Figures 3.8 and 3.9, respectively.
Figure 3.8: PMI19002+3922 blue spectrum with best fit model overlaid in red.

Figure 3.9: PMI19002+3922 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a blue dotted line.
PMI19002+3922 has a total of 41 *Kepler* light curves for both long and short cadences observed over 17 and 8 quarters, respectively. The long cadence data does not show any periodic variations. All but one of the short cadence quarters also does not show any variations. Quarter 7 in the short cadence data shows periodic variations, but it is most likely contamination from a nearby source and has no bearing on the pulsation nature of this object. Figures 3.10 and 3.11 show the full range of photometric observations with a small section expanded to illustrate that no periodic variations were detected. A power versus period plot, produced from the NEA using the Lomb-Scargle method, is displayed in Figure 3.12 to illustrate that there was no strong periodicity found for PMI19002+3922. No strong peaks exist well above the noise in the periodogram plot, which is shown for periods we expect from pulsations (<1 day). For an example of strong periodicity, see §3.3.6.

![Figure 3.10: PMI19002+3299 long cadence light curve spanning 17 quarters.](image)

PMI19002+3922 is a known WD with main designations of WD1858+393 and EGGR 850. This WD was studied in the infrared using *Spitzer* photometry to try to find infrared excesses in white dwarfs (Farihi et al., 2008). The effective temperature found from infrared modeling is 9470 K, which does not match our preliminary results. No optical spectra or photometry was used to study this system, so this is the first
presentation of *Kepler* data of this WD and a confirmation of its DA white dwarf designation.

![Figure 3.11: PMI19002+3922 short cadence light curve spanning 8 quarters.](image)

**Figure 3.11:** PMI19002+3922 short cadence light curve spanning 8 quarters.

![Figure 3.12: NEA Lomb-Scargle plot of power versus period for PMI19002+3922, which does not show strong periodicity in the range of expected pulsation periods (<1 day).](image)

**Figure 3.12:** NEA Lomb-Scargle plot of power versus period for PMI19002+3922, which does not show strong periodicity in the range of expected pulsation periods (<1 day).

### 3.3.5 PMI19085+4338 (KIC 7879431)

Analysis of PMI19085+4338 spectra resulted in an effective temperature that is a few thousand Kelvin too hot to be a pulsator candidate. Models applied to the blue spectrum
yielded $T_{\text{eff}} = 15,000\ \text{K}$ with $\log g = 7.75$ and the red spectral models produced $T_{\text{eff}} = 15,000\ \text{K}$ with $\log g = 8.75$. The red and blue parameters are in statistical agreement for temperature and surface gravity. The model of the blue side of the spectrum fits the Balmer line profiles of H\(\beta\), H\(\gamma\), and H\(\delta\) well in both depth and shape. The H\(\alpha\) profile is fit very well including both the line profile and the continuum of the red spectra. Light curve data was not available for PMI19085+4338 to confirm the object is not a pulsator. Figures 3.13 and 3.14 display the blue and red spectra, respectively, along with the overlaid best fit model in red.

PMI19085+4338 is not found in SIMBAD, but five sources were found within 2′ of its RA and DEC. There were three KIC sources: KIC7879456, KIC7879433, and KIC7879384, a planet candidate, and a Tycho object labeled as a star. The three KIC objects’ apertures were searched to determine if PMI19085+4338 was found in the background, but it was not found in any of the three KIC objects. PMI19085+4338 is a newly discovered and classified non-pulsating DA white dwarf in the Kepler field.

Figure 3.13: PMI19085+4338 blue spectrum with best fit model overlaid in red.
3.3.6 PMI19141+4936 (KIC 11604781)

Figures 3.15 and 3.16 show blue and red observed spectra of PMI19141+4936, respectively, with the best fit model overlaid. Modeled parameters for the blue spectra give $T_{\text{eff}} = 21,000\, \text{K}$ with $\log g = 7.00$. The modeled parameters for the red spectra are in statistical agreement with the blue, providing $T_{\text{eff}} = 21,000\, \text{K}$ and $\log g = 7.50$. PMI19141+4936 has a mid-range effective temperature and low surface gravity, which does not place it in the instability strip. The blue spectrum has high signal to noise with deep, clean line profiles, most of which are fit quite well with the model. The continuum in the blue model is higher in intensity than the observed spectrum between the higher order Balmer lines.
Figure 3.15: PMI19141+4936 blue spectrum with best fit model overlaid in red.

Figure 3.16: PMI19141+4936 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line.
PMI19141+4936 was observed over 5 quarters in the long cadence mode and one quarter of the short cadence mode. Both the long and short cadence data exhibit small periodic variations, shown in Figures 3.17 and 3.18. The modeled temperature of PMI19141+4936 does not lend itself to being a pulsator, but the photometric data shows periodic variations. The LC curves were phased using the Lomb-Scargle method (periodogram shown in Fig. 3.20) to compute the most likely period (NEA), which yielded a period of 4.89 days. Figure 3.19 shows the long cadence light curve phased with a period of 4.89 days. The SC curve was put to the same method and produced a matching period of 4.88 days.

![Long Cadence Light Curve](image)

**Figure 3.17:** PMI19141+4936 long cadence light curve spanning 5 quarters.

PMI19141+4936 was classified as a DA white dwarf by Øsetensen et al. (2011). There is a large discrepancy between Øsetensen et al. (2011) and our measurement of the effective temperature and log g. Øsetensen et al. (2011) finds $T_{\text{eff}} = 9.1(5)$ kK and $\log g = 8.3(3)$ dex. Our measurements are only preliminary and this discrepancy will be investigated in follow-up studies of our white dwarfs. Øsetensen et al. (2011) also observes the $\sim$5 day periodic variations of PMI19141+4936 and cannot determine why the variations are seen. The periodic variations are too long for an average DA WD pulsator and there is no clear indication in the data of a companion or a magnetic field.
The periodic variations observed in PMI19141+4936’s light curve cannot be from g-mode pulsations because the κ- and γ-mechanisms cannot occur in a DA white dwarf with our modeled effective temperature. Our estimate of the temperature is too hot for a partial hydrogen ionization zone to exist in this white dwarf (the estimate from Østensen et al. (2011) could still provide a partial ionization zone of hydrogen). The spectra in our work does not quite look like a normal DA white dwarf, but more information and study is necessary. Østensen et al. (2011) claims that if there is a companion it would have to be either non-stellar and not show any variations in the optical regime. PMI19141+4936 is not confirmed as a DA white dwarf and the periodic signal observed cannot be due to pulsations, if it is a white dwarf.
Figure 3.19: PM19141+4936 phased long cadence light curve.

Figure 3.20: NEA Lomb-Scargle plot of power versus period for PM19141+4936, which shows extremely strong periodicity at 4.89 days.
PMI19173+4452 is not predicted to be a pulsator because the effective temperatures derived from both the blue and red spectral analysis do not fall within the instability strip. Parameters from modeling the blue spectra yield $T_{\text{eff}} = 22,000$ K with $\log g = 8.25$ and the red spectra yield $T_{\text{eff}} = 22,000$ K with $\log g = 7.75$. The parameters from the red and blue model fits are in statistical agreement and produce an effective temperature too hot for pulsations to occur. The observed blue spectrum of PMI19173+4452 has high signal to noise and shallower and broader line profiles, in comparison to some of the previous, lower temperature white dwarfs (Fig. 3.21). The model does not fit the H$\beta$ line profile very precisely, especially in the shape of the wings. H$\gamma$ and H$\delta$ are fit well, except for a small deviation of the observed spectrum from the model in the blue wing of H$\gamma$. The general trend is followed throughout the observed spectrum and the model continuum matches well to H$\gamma$. The H$\alpha$ line profile is fitted very well with the model through the continuum, where the wings of H$\alpha$ are also fit well (Fig. 3.22).

Figure 3.21: PMI19173+4452 blue spectrum with best fit model overlaid in red.
Figure 3.22: PMI19173+4452 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line.

Figure 3.23: PMI19173+4452 long cadence light curve spanning 6 quarters.

PMI19173+4452 was observed during six quarters in the long cadence mode and two quarters in the short cadence mode. No periodic variations were observed over those time periods (see Figs. 3.23 and 3.24). Observing no periodic variations confirms the claim that PMI19173+4452 is not a pulsator, agreeing with the modeled parameters.
produced from the blue and red spectral analysis above. Figure 3.25 shows a periodicogram produced by NEA of power versus period and shows no prominent periodicity in the light curve for PMI19173+4452. In the literature a pulsation candidate survey was conducted by Østensen et al. (2010) and it was noted that PMI19173+4452 is a DA white dwarf and is not a pulsator. Here we confirm PMI19173+4452 as a DA white dwarf and a non-pulsator.

Figure 3.24: PMI19173+4452 short cadence light curve spanning 2 quarters.

Figure 3.25: NEA Lomb-Scargle plot of power versus period for PMI19173+4452, which does not show strong periodicity in the range of expected pulsation periods (<1 day).
3.3.8 PMI19179+4524 (KIC 9082980)

Spectral analysis of the blue spectra of PMI19179+4524 produced $T_{\text{eff}} = 13,500$ K with log g = 8.00, an effective temperature a bit too hot to fall within the instability strip. Analysis of the red spectra is in statistical agreement with the blue, with $T_{\text{eff}} = 13,750$ K and log g = 7.25. The red spectra could not be fit very well because of the noisy continuum and low signal to noise within the H$\alpha$ line profile itself. The blue spectrum fits H$\gamma$ the best, with the modeled profile of H$\delta$ being too narrow for the observed spectrum profile. The H$\beta$ profile was not fit well in shape, and the continuum between H$\beta$ and H$\gamma$ also does not fit well. The blue and red spectra with respective model fits can be seen in Figures 3.26 and 3.27. No light curves are available for PMI19179+4524, but this WD is not a pulsator based on the parameters determined from the spectral analysis above.

PMI19179+4524 was not found in SIMBAD and two objects were found within 5' of its RA and DEC. One object is a planet candidate and the other is a Tycho object labeled only as a star with alternate designation KIC9015738. The aperture and background of KIC9015738 was searched to determine in PMI19179+4524 was within the field, but it was not found. PMI19179+4524 is a newly discovered and classified non-pulsating DA white dwarf in the Kepler field.
Figure 3.26: PMI19179+4524 blue spectrum with best fit model overlaid in red.

Figure 3.27: PMI19179+4524 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line.
From the spectral analysis of the blue spectrum of PMI19245+3734, we predict this WD is not a pulsator, as it is slightly hotter than the upper edge of the instability strip. The best fit model of the blue spectra of PMI19245+3734 yielded $T_{\text{eff}} = 13,000 \, \text{K}$ and $\log g = 8.00$, and the best fit model for the red spectra yielded $T_{\text{eff}} = 13,000 \, \text{K}$ and $\log g = 7.00$. Figure 3.28 displays the best fit model for the blue spectra of PMI19245+3734, showing a good fit for H$\beta$, H$\gamma$, and H$\delta$ in shape and depth. The blue continuum is fit well throughout the blue spectrum, with a small flux differential between H$\beta$ and H$\gamma$. The red continuum was difficult to fit and the H$\alpha$ profile is not fit well in depth and shape through the wings (Fig. 3.29).

**Figure 3.28:** PMI19245+3734 blue spectrum with best fit model overlaid in red.

PMI19245+3734 was observed over four quarters in the long cadence mode. As seen in Figure 3.30, no periodic variations are present, which agrees with the modeled
spectral parameters, which do not indicate PMI19245+3734 is a pulsator. No short cadence data was available for this white dwarf. Figure 3.31 displays an NEA periodogram of power versus period to show that no strong periodicity is present in PMI19245+3734.

**Figure 3.29:** PMI19245+3734 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a blue dotted line.

PMI19245+3734 is a known DA white dwarf and is classified as such in SIMBAD. The references associated with the object, however, do not include PMI19245+3734 in the paper where it is supposed to be classified. The object is found as a proper motion target in the LSPM catalogue (Lépine & Shara, 2005), but it is not classified as a WD in this paper. PMI19245+3734 is confirmed as a non-pulsating DA white dwarf.
Figure 3.30: PMI19245+3734 long cadence light curve spanning 4 quarters.

Figure 3.31: NEA Lomb-Scargle plot of power versus period for PMI19245+3734, which does not show strong periodicity in the range of expected pulsation periods (<1 day).
3.3.10 PMI19409+4240 (KIC 7129927)

We do not expect PMI19409+4240 to be a pulsator with modeled parameters derived from the analysis of the blue spectra yielding $T_{\text{eff}} = 18,750$ K and $\log g = 7.25$. Analysis of the red spectra agrees with the blue analysis, producing $T_{\text{eff}} = 19,750$ K and $\log g = 7.00$. The red parameters support the hypothesis that PMI19409+4240 is not a pulsator. Figures 3.32 and 3.33 display the blue and red spectra with the best fit models overlaid, respectively. The blue model fits the line profiles of H$\beta$, H$\gamma$, and H$\delta$ in shape, with some discrepancy in the wings of H$\gamma$ and H$\delta$. The continuum is fit well except between H$\gamma$ and H$\delta$, where the observed spectrum makes a dip, which the model does not match. The red model spectrum fits H$\alpha$ well in shape, depth, in the wings, and the continuum’s general trend is matched well.

![Graph](image)

**Figure 3.32:** PMI19409+4240 blue spectrum with best fit model overlaid in red.

PMI19409+4240 was observed over three quarters in the long cadence mode and one quarter in the short cadence mode. Figures 3.34 and 3.35 show the long and short cadence observations, respectively, which do not exhibit any periodic variations. The photometric data analysis agrees with the spectral analysis to show that PMI19409+4240...
is not a pulsator.

Figure 3.33: PMI19409+4240 red spectrum with best fit model overlaid in red the best fit model for the corresponding blue spectrum overlaid as a yellow dotted line.

PMI19409+4240 is a known WD and was found to possibly be a WD binary composed of two DA white dwarfs (Øsetensen et al., 2011). Øsetensen et al. (2011) claims that the cores are not fit well for any temperature and gravity and that the

Figure 3.34: PMI19409+4240 long cadence light curve spanning 3 quarters.
spectrum is actually a composite of a DA2 and a DA3 WD. This WD will also be studied more in depth in future studies, in an attempt to confirm the double WD claim.

**Figure 3.36:** NEA Lomb-Scargle plot of power versus period for PMI19409+4240, which does not show strong periodicity in the range of expected pulsation periods (<1 day).
3.4 Discussion

Spectral analysis of PMI18450+4800 produced an effective temperature of 11,750 K and surface gravity of $10^{8.25}$ cm s$^{-2}$, which places this WD in the instability strip. *Kepler* light curves were not available for PMI18450+4800, so we cannot confirm the pulsation nature of this DA white dwarf.

A search was conducted for objects close enough to PMI18450+4800’s position, so that the object could possibly be within the pixels surrounding another target. Unfortunately, no observed KIC object was found close enough to PMI18450+4800 in *Kepler* data. The ancillary data was also checked to determine if any data relating to the KIC number for PMI18450+4800 was found, but no data could be located. *Kepler* is no longer staring in the same field of view, so if a light curve is to be completed for PMI18450+4800, it will have to be from the ground. Although, with a $V$ magnitude of 18.7, it would be fairly difficult to obtain a high signal to noise light curve from ground based observatories without expending a tremendous amount of exposure time on the WD.

PMI19141+4936 was seen to exhibit periodic variations in its *Kepler* light curve, but spectral analysis did not place it within the instability strip. Spectral analysis of PMI19141+4936 produced an effective temperature of 21,000 K and surface gravity of $10^7$ cm s$^{-2}$. PMI19141+4936 cannot be exhibiting DA white dwarf pulsations with an effective temperature of 21,000 K.

The target pixel file for PMI19141+4936 was inspected to determine if there was a nearby source, which was contaminating the light curve. Surprisingly, there were no other sources within the TPF, so the periodic variability is in fact coming from PMI19141+4936. As discussed in §3.3.6, Øsetsen et al. (2011) also noticed the periodic variations, which did not logically match a pulsation period. No other optical
counterparts are visible on the TPF, so perhaps this WD has some sub-stellar companion, which does not emit enough radiation in the optical to be known as a source. We do not know the cause of the periodic variations in PMI19141+4936, but we do not predict this object to be a DA white dwarf pulsator. One hypothesis is that this object is not a DA white dwarf, but instead possibly a pulsating B giant.

Spectral analysis of the remaining eight of our DA white dwarfs produced effective temperatures greater than the instability strip and those with light curves did not show any periodic variation. Surface gravities ranged from log g = 7.50 dex to log g = 8.50 dex, for all ten of our objects and effective temperatures cooler than 30,000 K. Determining temperatures and gravities of WDs allow for age estimates, which in turn help to determine how long the WDs have been cooling and slowly evolving.

Conducting a simple, order of magnitude calculation, estimates of cooling ages were derived for our 10 WDs. Using the Stefan-Bolzmann equation, we calculated a luminosity using the modeled effective temperature and a radius of $5 \times 10^6$ m, as an average estimate of a WD radius. The luminosities were then converted into solar luminosity units, where $L_\odot = 3.846 \times 10^{26}$ W. The mass was estimated from the derived log g parameters, $M = \frac{gn^2}{G}$, and transformed into solar masses, where $M_\odot = 1.989 \times 10^{30}$ kg. Finally, the luminosity as a function of time equation from Hansen (2004) was rearranged to solve for the cooling time,

$$\left( \frac{t_{cool}}{10^9 \text{yr}} \right) \sim \left[ \frac{L}{8.4 \times 10^{-4}L_\odot} \left( \frac{M_\odot}{M} \right) \right]^{-5/7},$$

(3.1)

where $L$ is the luminosity of the WD, $M$ is the mass calculated from the log g parameter, and $t_{cool}$ is the cooling time. Several simple assumptions are made to get an order of magnitude cooling age for our white dwarfs. Table 3.2 shows the rough luminosity and age estimates for our white dwarfs. The derived masses are lower than $0.4M_\odot$ and are on the low end of typical WD masses. Typical WD luminosities range from $10^{-4}L_\odot$ to
1.0L☉, so the calculated luminosities on the order of 10⁻³L☉, are typical of average WD luminosities. However, these are order of magnitude estimates to illustrate that simple physics does give a rough idea of the physical parameters of a white dwarf.

Table 3.2: Order of magnitude estimates of WD cooling ages.

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<td>10⁻³ L☉</td>
<td>10⁶ yr</td>
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Chapter 4

V523 Lyrae

4.1 How Accretion Works in Cataclysmic Variables

Cataclysmic variables are semi-detached binary systems, meaning that there is active mass transfer from the secondary, to the WD primary (Fig. 4.1). Matter is accreted onto the WD through an accretion disk in the plane of the white dwarf’s equator. Accretion occurs when the secondary stars’ envelope fills its Roche lobe and material begins to flow from the secondary to the primary. A Roche lobe is an equipotential surface, which surrounds the star in a balloon-like shape (see Fig. 4.2). This shape is determined both by tidal distortion, which elongates the secondary pulling it towards the primary, and rotation, which tends to flatten the star along the axis of rotation. Secondary stars evolve and become distorted by the gravitational pull of the WD, eventually filling their Roche lobes. As the expansion continues, matter can no longer be contained within the equipotential surface, so it begins to leak out and transfer to the white dwarf (Warner, 1995). Mass transfer will continue as long as there is material in contact with the Roche lobe. Since matter is lost quite rapidly through the accretion process, the secondary

\[\text{\url{hubblesite.org/newscenter/archive/releases/1995/23/image/a/}}\]
star must evolve more quickly, or the star-Roche lobe system must shrink to account for the mass loss in order to continue mass transfer (Frank, King & Raine, 1985).

When matter begins to transfer to the WD, it moves through the L1 inner Lagrangian point, which is a saddle point in the gravitational potential of the system (Warner, 1995). Lagrangian points are stable or unstable points of gravitational potential between two masses where the “centrifugal” force is balanced (Carroll & Ostlie, 2007). There are five Lagrangian points in any binary system: L1, L2, L3, L4, and L5. Each Lagrangian point is located where an equipotential surface crosses itself. L1 is the inner Lagrangian point which lies between the two masses. L2 is an outer point, which lies at the same distance as L1, but on the opposite side of the star with the smaller mass. L3 is located on the outer side of the more massive object. These three Lagrangian points, L1, L2, and L3, are unstable points which occur at local maxima of the gravitational potential (Carroll & Ostlie, 2007). L4 and L5 are also local maxima which are equidistant from, and perpendicular to, a line connecting the two masses. These two points have equipotential surfaces which enclose teardrop-shaped areas. Figure 4.2 shows the shape of a typical Roche lobe, outlined in bold, and the placement of
the Lagrangian points in a semi-detached binary system. An example of the L4 and L5 points are the Trojan asteroids, which orbit on either side of Jupiter.

![Figure 4.2: Typical Roche lobe geometry for an semi-detached binary system and the location of the Lagrangian points (Frank, King & Raine, 1985).](image)

Accretion in CVs occurs through a disk which forms in the plane of the white dwarf’s equator from matter being transferred from the secondary. When the Roche lobe of the secondary is filled, matter is perturbed and forced through L1 into the Roche lobe of the primary. The material streams towards the WD, but since it already carries angular momentum with it from the orbital motion of the binary system, the material cannot accrete directly onto the white dwarf. As the material enters the Roche lobe of the WD, which is not filled, the material begins to fall into the gravitational potential well of the white dwarf. Since the material cannot accrete directly, it begins to orbit in an ellipse, acting like test particles in the gravitational potential of the white dwarf.
As more material comes through L1, the orbiting material connects with the point of inflow, thermalizes, and begins to act as a fluid instead of distinct particles. The thermalization circularizes the orbit of the material, which now orbits with the lowest energy it can with the given angular momentum. A ring of material is now created around the WD, orbiting with a specific angular momentum. As the matter continues to orbit, dissipation is likely, either through viscous perturbations, shocks, collisions, or other processes. When the material is perturbed, some of the matter will lose angular momentum, for example, causing material to begin to spiral in towards the white dwarf. Angular momentum from the in-spiraling material is transferred to the outer part of the ring, which causes the ring of material to spread both towards and away from the WD, creating a disk. Further perturbations will eventually allow matter to accrete onto the surface of the white dwarf from the innermost part of the disk (Frank, King & Raine, 1985).

Dwarf novae outbursts occur from thermal instabilities which arise in the disk from a combination of viscosity and magnetic turbulence. The disk is composed mostly of neutral and ionized hydrogen. Ionized hydrogen interacts with magnetic fields, causing blobs of material to move inwards and outwards in the disk, which transfers angular momentum. Accretion disks are fueled by the transfer of angular momentum from the inner to the outer edge of the disk. A thermal instability triggers an outburst by sending a heating wave through the disk, which propagates to each adjacent annuli of the disk. There are two options for the heating wave to produce an outburst, inside-out or outside-in. The inside-out wave occurs when the thermal instability occurs near the inner edge of the disk and causes angular momentum to be thrust outward, while funneling material inward to accrete onto the white dwarf. The outside-in wave starts with an instability near the outer edge of the disk, but still propels material inward and angular momentum outwards. Outburst shapes depend on how the heating wave is produced and how the temperature and surface density is affected during the outburst (Hellier,
2001). Outbursts are unique even within a single object, which produces outbursts regularly. The differences are caused by where the outburst is triggered from within the disk itself. In the following sections, we discuss the analysis of the spectroscopy and photometry of the CV, V523 Lyr.

4.2 V523 Lyr in the Literature

V523 Lyr was confirmed as an SU UMa type dwarf nova and ~240 days of Kepler data were presented and analyzed in Howell et al. (2013) (hereafter HES). However, the data presented in Figure 4 of HES, which is labeled as V523 Lyr, is not the light curve for V523 Lyr; there was an error in the labeling of V523 Lyr in HES. The object, which is an SU UMa system and is presented in HES is V516 Lyr; the analysis also applies for V516 Lyr and not V523 Lyr. This work was originally intended to be an extension of the work completed in HES, but is now the first presentation of the preliminary analysis and display of the full Kepler light curve of V523 Lyr. One other reference to the Kepler light curve of V523 Lyr is noted in a footnote in Kato & Osaki (2013), which also points out the fact that the light curve presented as V523 Lyr in HES is V516 Lyr.

Original classification of V523 Lyr included both DN and NL in Mochejska et al. (2003) and Kaluzny et al. (1997). Both Mochejska et al. and Kaluzny et al. see a large amplitude outburst, followed by heightened intensity including small amplitude outbursts in the heightened state. The large dip in brightness could be similar to what we see in some of the eclipse-like events we observe (quarters 6, 7, 9, 11, which will be discussed in the next section). Mochejska et al. observed V523 Lyr for a longer time than Kaluzny et al., but the large amplitude event is not seen again, only the small amplitude outbursts in what appears to be a high state (see Figs. 4.3 and 4.4). In our observations, discussed in the next section, we do not see a large amplitude event, only
Figure 4.3: Light curve of V523 Lyr, figure 3 from Kaluzny et al. (1997).

Figure 4.4: Light curve of V523 Lyr, figure 4 from Mochejska et al. (2003).

the following outbursts which look similar to those in the heightened state of Mochejska et al. (2003) and Kaluzny et al. (1997).

V523 Lyr and V516 Lyr are close to each other on the sky, but not close enough to be confused as the same source. V523 Lyr has a right ascension (RA) of 19:21:07.402 and a declination (DEC) of +37:47:56.53\(^2\), whereas V516 Lyr has an RA of 19:20:35.725 and a DEC of +37:44:52.29\(^2\). A finder chart from the Sloan Digital Sky Survey\(^3\) (SDSS) shown in Figure 4.5 illustrates the positions of V523 Lyr and V516 Lyr.

\(^2\)simbad.u-strasbg.fr/simbad/
\(^3\)skyserver.sdss.org/dr12/en/tools/chart/image.aspx

67
Figure 4.5: Finder chart from SDSS with the locations of V523 Lyr and V516 Lyr labeled.

4.3 V523 Lyr Photometry

Target pixel files were obtained from MAST\textsuperscript{4} located at the Space Telescope Science Institute (STScI), where the Kepler archive is housed and maintained. From several guest observer (GO) proposals, V523 Lyr was observed as a primary source, or in the background, over a total of 11 quarters, spanning about 2.5 years. V523 Lyr was only directly observed in 4 quarters (Q6-Q9), but was within the photometric aperture of NGC 6791 cluster members for an additional 6 quarters. V523 Lyr was just off the image for one quarter and is discussed in detail below. The full light curve is displayed in Figure 4.8 and the analysis is discussed below.

\textsuperscript{4}archive.stsci.edu
Dwarf nova outbursts are evident, marked by the sharp rise and decline in brightness of the V523 Lyr light curve, with outbursts lasting for several days. V523 Lyr does not exhibit superoutbursts or superhumps, therefore we claim that V523 Lyr is not an SU UMa type dwarf nova. Since it does not exhibit superoutbursts, we propose here that V523 Lyr is a dwarf nova, but of a different subclass. V523 Lyr exhibits multiple, quasi-periodic outbursts, so CNe, RNe, NL, and magnetic CVs are all ruled out. Recall that CNe only exhibit one outburst in their history and RNe have multiple outbursts similar in amplitude and structure to CNe, but separated by years. NLs are known as “non-eruptive” CVs, and there is no indication of a strong magnetic field. V523 Lyr could be a part of the Z Cam subclass, having not yet shown a standstill (extended high state). The U Gem subclass encompasses all other non-Z Cam and non-SU UMa dwarf novae. V523 Lyr is likely to be of the U Gem subclass, but the light curve does show some strange features, discussed below.

Figure 4.6: A zoomed in view of V523 Lyr and its location on the pixel file. The red circles are 4 non-KIC sources which are very close to V523 Lyr and could be contaminating its light curve.
There are four additional sources within the same pixel where V523 Lyr is located (see Fig. 4.6), in each TPF (target pixel file). Some contamination might exist from these sources nearby to V523 Lyr, but there was not much that could be done to eradicate the other sources from the light curve of V523 Lyr. These four sources are not found in SIMBAD, so we could not determine their magnitudes or characteristics to determine if they are a factor in contaminating V523 Lyr’s light curve. These sources are found from the PyKE task kepfield, and the fact that they cannot be found in SIMBAD might lead us to believe that they are faint enough to not be a contaminating factor in the V523 Lyr light curve. Only the single pixel, where V523 Lyr was located, was used to extract a light curve for each quarter. This was done in order to minimize contamination of nearby sources. Since V523 Lyr is located in the same region as NGC 6791 on the sky, it is in a crowded field, as shown previously in the top right panel of Figure 2.4 in §2.2.2. A nearby contaminating source, source A, showed a very periodic light curve, which leaked into the pixels containing the light curves for V523 Lyr in some quarters. Source A has an RA and DEC, which associates it with V634 Lyr, an ellipsoidal variable star (SIMBAD). Source A’s location is shown in Figure 4.7. The period of this object, 2.21 days, was calculated using NEA tools and was compared to attempted calculations of V523 Lyr’s orbital period (discussed below).

The LC light curve for V523 Lyr was extracted using the methods described in §2.2.2 and can be seen in Figure 4.8; the SC light curve over 2 quarters can be seen in Figure 4.9. The difference in amplitude of the outbursts between the LC and SC observations is due to the smoothing effects of the SC light curve in order to easily visualize the trends. Twenty eight outbursts were observed from Kepler; a few might be missing, or show partial outbursts, due to interruptions in data collection. For Q13, it was found that V523 Lyr lies just outside of the pixels collected for KIC 100004034 (see Fig. 4.7). A light curve was extracted from the edge pixels close to where V523 Lyr was located, but the light curve of the single pixel where V523 Lyr actually lay
was not available for extraction. The data ranges over 11 quarters from Q6 to Q16, but we only have single pixel light curves for 10 out of the 11 consecutive quarters. The Q13 light curve is included in the full light curve, but we note here that it is not the best extraction we could have done, however the light curve clearly shows outbursts consistent with V523 Lyr (see Fig. 4.8). Outburst measurements of V523 Lyr are listed in Table 4.1. The average outburst duration is $\sim$9 days and the average time between outbursts is $\sim$25 days. DNe outbursts in general are not reproducible because they are slightly different for each occurrence. There are four types of outbursts, classes A, B, C, and D. Class A exhibit the quickest ascent from quiescence to peak, $\sim$2 days, whereas class D exhibits the slowest rise to outburst, $\sim$10 days, with classes B and C having intermediate rise times. The rise times are correlated with the quiescent magnitude between outbursts (Warner, 1995). V523 Lyr falls under class B or C, as the rise times are between $\sim$3 and $\sim$6 days.

Once the full light curve, over 1020 days, was normalized using techniques discussed in §2.2.2, the outbursts were removed in order to attempt to calculate the orbital
period. Semi-periodic modulation between outbursts can be seen in Figure 4.10, which is an example of the quiescent regions from quarter 7. An attempt was made at extracting a period from this modulation, by the Lomb-Scargle method, to determine the orbital period of the CV. However, the modulation is not quite periodic, so several periods could be extracted from the data. Of the attempted extracted periods, we determined that best period was $\sim 5$ days, which is about twice as long as source A’s period. The semi-periodic variations in the light curve between outbursts occur too infrequently to be representative of the orbital period and also to be contaminated by source A’s variability. The orbital period of a CV should be of order a few hours, so this quasi-periodic modulation in quiescence is not indicative of the orbital period, but of one other process. We will continue to analyze V523 Lyr’s light curve, as it is very unique and complex. We also point out the large dips after some of the outbursts, as seen in Q6, Q7, Q9, Q11, and possibly Q16 in Figure 4.8. The cause of these dips below the usual continuum at quiescence is unknown. There are many mysteries about V523 Lyr, but here we have presented the full *Kepler* light curve and preliminary analysis.

<table>
<thead>
<tr>
<th>Table 4.1: Table of outburst measurements of V523 Lyr.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
</tr>
<tr>
<td>Days</td>
</tr>
<tr>
<td>Peak-to-Peak</td>
</tr>
<tr>
<td>Between Outbursts</td>
</tr>
<tr>
<td>Duration</td>
</tr>
<tr>
<td>Rise to Peak</td>
</tr>
<tr>
<td>Decline from Peak</td>
</tr>
</tbody>
</table>

The quasi-periodic modulation observed in the quiescent parts of the V523 Lyr light curve can be checked by executing the Lomb-Scargle method on pixels adjacent to V523 Lyr for each quarter to determine if any quasi-periodic signals are calculated. If there is a nearby object creating the $\sim 5$ day period, the periodicity should show up in neighboring pixels as well as at all times during the light curve. It is possible that
during the outbursts we do not see the quasi-periodic signal because it is drowned out, or this quasi-periodicity is actually associated with V523 Lyr.

In order to illustrate the similarities and differences of V523 Lyr to other typical dwarf novae, we have over plotted a few typical outbursts of U Geminorum and SS Cygni (Figs. 4.11 to 4.13). U Gem and SS Cyg are two dwarf novae that have been studied for over 100 years, so their outbursts are well characterized. The U Gem and SS Cyg light curves were obtained from AAVSO\(^5\) (American Association of Variable Star Observers), which houses observations of U Gem, SS Cyg, and thousands of variable stars from observers all over the country. The U Gem and SS Cyg outbursts are normalized to the continuum of each V523 Lyr outburst for comparison. SS Cyg has two characteristic outburst shapes, whereas U Gem has one. One of the SS Cyg outbursts is very similar to the U Gem outburst; the other is shorter in duration and smoother. Figures 4.11 and 4.12 display the outbursts of U Gem and SS Cyg scaled down to compare the actual shapes of the outbursts. Figure 4.13 displays the full magnitude of U Gem and SS Cyg outbursts compared to the modulation of V523 Lyr, where there is a large difference in outburst magnitudes. The magnitudes of V523 Lyr are Kepler magnitudes using the conversion \( K_p = -2.5 \log \left( \frac{L_{\text{obs}}}{L_{\odot}} \right) + 12 \), taken from the Kepler GO website and the magnitudes of U Gem and SS Cyg are in the V band.

\(^5\)www.aavso.org
Figure 4.8: Full normalized LC light curve of V523 Lyr from quarter 6 to 16.
Figure 4.9: V523 Lyr short cadence light curve for quarters 9 and 15. The data has been filtered with a low bandpass to smooth it out in order to see features more clearly.
Figure 4.10: Example of the quiescent parts of the V523 Lyr light curve (from Q7).

Figure 4.11: U Gem (left) and SS Cyg (right) outbursts scaled down to compare the shape against outburst number 5 from our V523 Lyr light curve. The x-axis only applies to the V523 Lyr light curve.
Figure 4.12: SS Cyg outbursts compared to three different outbursts of V523 Lyr (outburst 5 (top left), 6 (top right) and 7 (bottom)). The x-axis only applies to the V523 Lyr light curve.

Figure 4.13: Comparison of full outburst magnitudes for the two outbursts of SS Cyg show that SS Cyg has a much larger change in magnitude at outburst (∼3.5 mags) than V523 Lyr exhibits (≤ 1 mag). The x-axis only applies to the V523 Lyr light curve.
4.4 V523 Lyr Spectroscopy

Table 4.2 shows the spectral observation data for V523 Lyr. The 200" spectra were taken after the original Kepler mission failed, so unfortunately, we do not have coincident spectra and light curves as in HES. A total of 12 observations in both the blue and red separately, were completed and analyzed. Each spectrum was analyzed individually to show the differences over each night. Figure 4.14 shows the blue spectra over both nights.

<table>
<thead>
<tr>
<th>Obs Date</th>
<th>Obs Time</th>
<th>Exp Time</th>
</tr>
</thead>
<tbody>
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<td>02-07-2013</td>
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</table>

of observations. The sums of all the observations taken during each night are shown in Figures 4.15 and 4.16, where the emission cores in Hγ and Hδ are seen clearly. A sample red spectrum is displayed in Figure 4.17. Another example of a red spectrum is shown in Figure 4.18, which was taken simultaneously with the blue spectrum which shows Hβ in emission during the night of 02 Jul 2013. The red spectra were very noisy and had cosmic rays or bad sky subtractions throughout each spectrum, so they could not be stacked over the observation period. The observations on each night were taken over about a period of two hours, so we should have observed the system at a few different times in its orbit, with the assumption that its orbital period is on the order of a few
hours. However, we were unable to constrain the orbital period, so we may only be seeing a fraction of the orbit.

Broad absorption with possible emission cores in H\(\delta\) and H\(\gamma\), with H\(\beta\) in emission, shows that V523 Lyr is probably on the rise of an outburst. Usually DNe show Balmer emission lines in their spectra at minimum, but as the system goes into outburst, the emission lines gradually turn to absorption lines and at maximum the spectrum is featureless. An example shown in Figure 4.19, displays the spectra of SS Cyg, a dwarf nova, as it rises from quiescence to outburst maximum. The spectra evolve over time from emission lines to almost featureless. This occurs because the emission line features get drowned out by the continuum emission from the disk, which rises as the system goes into outburst (Warner, 1995). V523 Lyr could possibly be near an outburst maximum when the emission line cores are seen, but they are very weak and only in a few observations. H\(\alpha\) can be seen in emission, as it is here, even when the rest of the Balmer series is in absorption, because of the physics of the hydrogen Balmer lines (Warner, 1995). The spectral features we see in the V523 Lyr spectra come from the accretion disk, and not the WD primary. We do not see the broad, deep, clean Lorentz profiles of the hydrogen Balmer lines in the V523 Lyr spectra, like we see from the spectra of our DA white dwarfs in Chapter 3.
Figure 4.14: Stacked blue spectra of V523 Lyr from both nights of observations in chronological order from top to bottom. The red dotted lines, from right to left, show the positions of H\(\beta\), H\(\gamma\), and H\(\delta\).
Figure 4.15: Summed spectrum of all the observations taken on the night of 01 Jul 2013. Emission cores can be seen in Hγ and Hδ.

Figure 4.16: Summed spectrum of all the observations taken on the night of 02 Jul 2013. Emission cores can be seen in Hγ and Hδ.
Figure 4.17: An example of a red spectrum of V523 Lyr from 01 Jul 2013. The red dotted line is the wavelength at which Hα occurs.

Figure 4.18: The corresponding red spectrum for the 02 Jul 2013 blue spectrum, which shows Hβ in emission. The red dotted line denotes the position of Hα.
Flux calibrated spectra from both nights of V523 Lyr were over plotted on top of each other to determine if there was any visible change in flux from observation to observation. The observations fluctuated back and forth within a range of $\sim$1 magnitude in the continuum, but there was no clear indication of flux increase or decrease corresponding to the rise and/or decline of an outburst.

4.5 Discussion

V523 Lyr is not confirmed to be an SU UMa type system of the dwarf nova class of cataclysmic variables. As noted in §4.2, a comparison of our measurements of V523 Lyr could not be completed because the analysis in HES was completed for V516 Lyr, instead of V523 Lyr. V523 Lyr is predicted to be a dwarf nova of the U Gem subclass. Outbursts are quasi-periodic, distinct, but occur on time scales of dwarf novae. Outbursts in V523 Lyr occur every $\sim$25 days over the observed $\sim$1020 day time period, and last $\sim$9 days.
Outburst rise times and durations are near the long end of the range of usual times, but V523 Lyr is a unique system. The dips below the continuum, observed in a few of the quarters, could be an opaque clump of disk material that we observe eclipsing. The dips are not periodic and do not occur consistently across the timeline of observations. V523 Lyr needs to be studied more in depth to determine if this system is in fact a CV, what causes the anomalies in the light curve, and to determine the fundamental parameters of the system.

Measurement of the orbital period of V523 Lyr was attempted, but a clear and valid period could not be calculated. The background and surrounding sources are possibly contaminating the light curve of V523 Lyr because the field is very crowded. This crowding causes leakage of light from nearby sources into the pixel where V523 Lyr lies, causing contamination of the light curve. We suspect that the periodicity seen in the quiescent part of the light curve is in fact due to a nearby variable system. The closest period able to be extracted from the quiescent parts is \( \sim 5 \) days. This calculated period does not match that of a usual CV, which usually have orbital periods of order a few hours. These quasi-periodic episodes could be small perturbations in the accretion disk, or an after shock-like event after each outburst. The calculated period is also not close to the period of 2.21 days calculated for source A. Source A is probably not contributing enough contamination to show up as a periodicity in the light curve of V523 Lyr.

We infer from the light curve, that V523 Lyr has low inclination, as there are no periodic eclipses observed. V523 Lyr has similar outburst shapes to both U Gem and SS Cyg, but there is a physical process occurring in V523 Lyr, which is not occurring in either U Gem or SS Cyg. We also infer that V523 Lyr, at the time of spectral observations, was on the rise of an outburst. At quiescence, DNe usually show the hydrogen Balmer series in emission, but as seen in §4.4, most of the Balmer series is in
absorption. Hγ and Hδ are in absorption, with Hβ ranging from emission to absorption. Hα however, is in emission in most of the spectra over the two nights.

V523 Lyr is a possible member of the open cluster, NGC 6791. EU Cancri is the only confirmed CV that is a member of a cluster, M67 (Gilliland et al., 1991). If V523 Lyr is a member of NGC 6791, this would have important implications for the evolution of the system. Clusters are composed of several hundreds of millions of stars which all formed around the same time. This would constrain an age for V523 Lyr, which allows us to learn about the evolution of the system. Age constraints are difficult to derive for CVs because they are interacting systems, so the evolution is convoluted due to the interactions. Ages of stars are important in the study of stellar and Galactic evolution. Constraining an age and distance for a CV would greatly increase our understanding of the evolution of interacting binaries.
Chapter 5

Conclusion

Only a handful of white dwarfs were known in the *Kepler* field when the spacecraft was launched. We have confirmed the WD status of 4 previously identified DA white dwarfs and added 5 newly identified DA white dwarfs, to the known Galactic WDs and to the known objects in the *Kepler* field. Table 5.1 summarizes the results for our DA white dwarfs; starred WDs are those that were able to be confirmed with *Kepler* photometry.

One of our ten DA white dwarfs is predicted to be a pulsator, PMI18450+4800, and another one of our objects shows periodic variations in its light curve, PMI19141+4936.

We need to obtain photometric data of PMI18450+4800 to confirm its pulsation nature and to study the pulsation modes if it is confirmed. PMI19141+4936 varies over 4.89 days, but the spectrum does not appear to show a companion; it does not look quite like a normal DA white dwarf and more information and research is required. There was no visible contamination of the light curve of PMI19141+4936 from a nearby stellar source. The photometric data was taken over \(~450\) days, almost uninterrupted, so the periodic variability is unlikely to be due to a chance event.

Although we only found one possible pulsator, we have provided preliminary effective temperature and gravity estimates for our 10 DA white dwarfs. All ten of our DA
white dwarfs have effective temperatures between 11,750 K and 22,000 K with surface gravities ranging from 7.00 dex to 8.25 dex. Further study of all our WDs, but especially PMI18450+4800 and PMI19141+4936, will provide an in depth look at some interesting and unique objects.

**Table 5.1:** Results table of DA white dwarfs.

<table>
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<th>Name</th>
<th>$T_{\text{eff}}$</th>
<th>$\log g$</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
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<td>8.25</td>
<td>$T_{\text{eff}}$ within the instability strip</td>
</tr>
<tr>
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<td>not a pulsator</td>
</tr>
<tr>
<td>PMI18553+4755</td>
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</tr>
<tr>
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<td>7.75</td>
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</tr>
<tr>
<td>PMI19141+4936*</td>
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<td>7.00</td>
<td>periodic variations in light curve</td>
</tr>
<tr>
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<td>8.25</td>
<td>not a pulsator</td>
</tr>
<tr>
<td>PMI19179+4524</td>
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<td>8.00</td>
<td>not a pulsator</td>
</tr>
<tr>
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<td>8.00</td>
<td>not a pulsator</td>
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<td>PMI19409+4240*</td>
<td>18750</td>
<td>7.25</td>
<td>not a pulsator</td>
</tr>
</tbody>
</table>

For V523 Lyr, we provide a preliminary study of the outbursts and physical parameters of the system. We have identified the true V523 Lyr source and light curve, but the light curve is challenging to understand. We hypothesize that V523 Lyr is a dwarf nova of the U Gem subclass, with outbursts occurring every $\sim$25 days and lasting $\sim$9 days. Outbursts occur quite regularly over a period of about 1000 days, with an unexplained reason as to the drop in intensity below the continuum after select outbursts. Further analysis needs to be completed in order to fully characterize V523 Lyr. We would like to obtain spectra at quiescence to determine if V523 Lyr really is a CV of the DNe class, which exhibits the hydrogen Balmer series in emission at quiescence. The orbital period of V523 Lyr, which should be of order a few hours, could not be determined from the light curve at quiescence. However a $\sim$5 day period, which is too long to be the orbital period of a CV, was extracted from the quiescent data. From the spectral analysis, we hypothesize that V523 Lyr was on the rise of an outburst when our spectral data was taken.
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91