University of Texas at Austin

Senior Year Thesis

White Dwarf Astronomy and the Freshman Research Initiative

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ABSTRACT

Pulsating white dwarf stars provide vast amounts of information in nearly every field of astronomy. Using precision asteroseismology, we can explore, for example, a star's mass, rotation rate, equation of state, and nuclear reaction rates. By studying the rate of change of WD pulsations we can explore galactic time measurements, orbiting planets, dark matter theories, or interior crystallization. Yet, to obtain accurate pulsation measurements, astronomers require long stretches of time-resolved data often spanning years. Thus, telescope time and travel funds often are the greatest constraint placed on WD pulsation studies. I believe the MONET telescope can help alleviate this problem. The MONET telescope is a remotely controlled 1.2m telescope operated by the Georg-August-Universität Göttingen and McDonald Observatory. By using the MAT-LAB oriented MAESTRO reduction process, I have successfully created a pipeline for producing accurate Fourier transforms of known WD pulsators using the MONET telescope. By comparing similar runs in similar weather conditions, the 82 telescope produces only roughly twice the signal-to-noise as the MONET. The accessibility of the MONET creates a number of scientific advantages. For example, time critical data can be obtained quickly without waiting for scheduled 82 observing runs. Moreover, data can be obtained evenly throughout the year rather than every few months. Finally, the MONET allows for telescope use by undergraduate astronomy students.

White dwarf stars can also provide ample amounts of information if they are part of an eclipsing binary system. NN Serpentis is a short-period eclipsing binary containing a hot hydrogen-rich white dwarf and a larger, cool red dwarf star. The system likely resulted when the more massive component evolved to a giant and engulfed the orbit of its companion. This common envelope phase laid bare the newly born white dwarf and substantially shortened the orbital period. Because NN Serpentis possesses such deep and well-defined eclipses, we can measure the mid-eclipse times to an accuracy of 100 ms or better. Using published, reanalysed, and new mid-eclipse times obtained from telescopes such as the 2.1 meter at McDonald Observatory, we investigated the long-term eclipse time variations present in NN Ser. Ultimately, we found excellent agreement with the light-travel-time effect produced by two additional planets orbiting the system with orbital periods of 15.5 and 7.7 years. There exist two equally intriguing explanations for the existence of planets in such a violent system. They could have formed before the white dwarf star's final stages, miraculously surviving its final death throes. Alternatively, the two planets could be second generation, forming from the remnants of the dying star like a phoenix rising from the ashes. The answer to this mystery could have vast implications for the field of planetary formation and stellar evolution.

Contents

1. Introduction

1.1. White Dwarf Stars

1.1.1. The death of a star

Our sun, as with the inhabitants of its solar system, has a finite lifetime. Six billion years from now, distant aliens looking upon our solar system will not see the familiar middle-aged star providing the earth with life-sustaining warmth, but rather an extremely hot and dense white dwarf. The sun's fate is not unique, however, as roughly 97% of all stars in the universe will too, in time, become white dwarfs. The story of a white dwarf, thus, begins with the death of a star.

The majority of stars, so called "main sequence stars", are fueled by nuclear reactions occurring in their core. Such stars are held intact by hydrostatic equilibrium, whereby the

Fig. 1.—: The Cats Eye planetary nebula. The ejection of the star's outer layers leaves behind a hot, degenerate white dwarf which was once the original star's core.

massive inward force of gravity is counterbalanced by an outward force due to the radiation pressure emanating from its core. Most of the star's lifetime is spent fusing four hydrogen nuclei into a single helium nucleus through the proton-proton chain. Each time this process takes place, roughly .7% of the combined hydrogen nuclei mass is converted into energy as described by the famous equation E=mc^2. Once stars $\gtrsim 0.4M_{\odot}$ run out of hydrogen in their core to fuse, they expand into a red giants. Due to much higher core temperatures, they can now fuse the remnant helium nuclei into carbon and oxygen. After a series of red giant evolution phases whereby the helium fuel in the core is depleted, stars between $0.4M_{\odot}$ and $4M_{\odot}$ expel their outer layers in a planetary nebula (see Figure 1). Eventually, all that remains is the extremely hot and dense original core composed primarily of carbon and oxygen. A white dwarf is born.

1.1.2. "The impossible star"

The history of white dwarf star astronomy is a wonderful example of the interplay between the seemingly unrelated fields of quantum physics and astronomy. In 1844, the German mathematician and astronomer Friedrich Bessel observed very slight changes in position of the star Sirius, concluding that an unseen binary companion must be present. It wasn't until 1915, however, that Walt Adams was able to constrain the mass and radius of this faint star using the newly built 1.5m reflecting telescope at Mt. Wilson Observatory. By using spectroscopic lines to determine the star's temperature, Adams determined the size of

Sirius B to be roughly that of the earth. This generated confusion in the astronomy field. Observations of the binary's orbit earlier determined Sirius B's mass to be approximately .94 $M_{\odot}$; Sirius B thus had a density roughly 25,000 times greater than the sun! Such densities are only possible if the star is not composed of neutral atoms, as in our sun, but rather is a compressed plasma comprised of unbound nuclei and electrons. Temperatures within these stars are not high enough to sustain nuclear reactions, and thus they must inevitably cool and expand. Yet, without any source of pressure directed outward, the star must actually do work *against* gravity, thereby violating the Second Law of Thermodynamics. This mystery led the great Sir Walter Eddington to refer to Sirius B as "the impossible star". A decade later, this mystery was solved by the astrophysicist Ralph H. Fowler and his student Subrahmanyan Chandrasekhar with the modern invention of quantum mechanics. According to the Pauli Exclusion Principle formulated in 1925 by Wolfgang Pauli, no two electrons can simultaneously occupy the same quantum state. Two years later, Werner Heisenberg published his Uncertainty Principle, which states

$$\Delta x \Delta p \geq \hbar/2 \tag{1}$$

where Δx is the uncertainty in position, Δp the uncertainty in momentum and $\hbar$ the reduced Planck constant. As electrons become increasingly compressed under the extreme pressure conditions in a white dwarf, the uncertainty in an electron's position Δx becomes ever smaller. Hence, under the Uncertainty Principle, the electrons must have a large uncertainty in momentum. Yet according to Pauli's exclusion principle, these electrons must *also* have different momentum than other surrounding electrons. This necessarily pushes electrons towards large momentum and therefore large pressure. Thus, white dwarf stars provided one of the first physical confirmations of the fledgling quantum mechanics theory.

1.1.3. White dwarf structure and cooling

We classify white dwarfs into different "flavors" based on the spectroscopically identified composition of their atmospheres. Most white dwarf are (thought to be) composed of carbon and oxygen ions in their cores. DA white dwarfs, the first discovered and most common (∼80%), have atmospheres of pure hydrogen. DB white dwarfs (∼16% of all WDs) show only He I lines in their spectrum while DO white dwarfs display strong HeII lines. Around 1% of WDs show no hydrogen or helium in their atmospheres, but rather exhibit only carbon lines (DQs) or other heavier elements (DZs). Perhaps the most unique of WD flavors are PG 1159 stars, named after the first such discovered, which have absolutely no hydrogen lines, weak HeII lines, and strong lines of ionized carbon and oxygen. It is thought these stars are the exposed core of a white dwarf, yet their evolution is still unknown (see Figure 2).

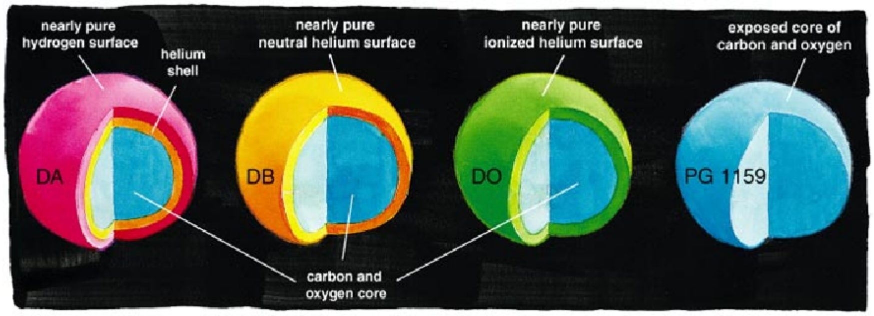


Fig. 2.—: White dwarfs come in a variety of "flavors" determined by their atmospheric composition. Nearly all white dwarfs are believed to contain a core of carbon and oxygen (blue). DA, DB and DO stars have nearly pure atmospheres of H, He or HeII respectively. PG 1159 stars appear to be partially exposed white dwarf cores (Kawaler & Dahlstrom 2000).

Importantly, while WDs may come in different flavors, their layers are extraordinarily chemically pure due to gravitational settling, making their structures relatively uncomplicated. For hot, young white dwarfs, theory suggests that energy loss is dominated by the emission of plasmon neutrinos. As the white dwarf cools, the heat capacity becomes almost entirely due to the thermal motion of its ions. Leon Mestel showed in 1952 that the cooling of a WD can be modeled, to a high degree of accuracy, as an insulating classical ideal gas surrounding a degenerate electron core (Mestel 1952). Later refinements would later come from the addition of neutrino energy loss, internal convection, gravitational contraction, residual nuclear burning and interior crystallization. With this direct relation between the age and temperature of a white dwarf, astronomers have been able to determine the ages of various stellar populations. This white dwarf cosmo-chronology was first demonstrated by Winget et al. 1987 to study the age of the galactic disc using the observed steep drop off in the population of cool WDs.

1.1.4. White dwarf pulsations

Most, if not all, stars in the universe pulsate. Stars like our sun pulsate primarily in radial pressure-modes (p-modes). These radial waves are caused by changes of temperature in the star's outer layers; as the gas cools it contracts and as it absorbs heat the gas expands. These contractions and expansions generate pressure waves which travel throughout the sun.

White dwarfs, in contrast, pulsate in non-radial g-modes where gravity, or buoyancy, is the restoring force. Any fluid, such as within a white dwarf, always wants to remain at a position of equilibrium where there are no forces causing it to rise or sink. Yet, within a

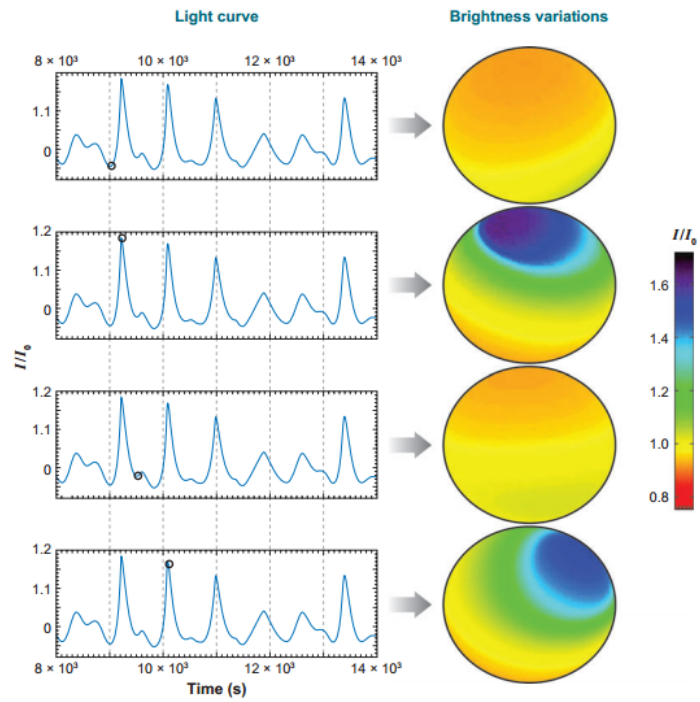


Fig. 3.—: Simulations of pulsations in the DBV star GD 358. Changes in the observed flux of the white dwarf on the left corresponds to surface brightness changes modeled on the right. Calculations and figure courtesy of Mike Montgomery

white dwarf, slight changes in temperature and pressure cause the fluid to vertically move up or down. In attempting to correct for this motion, this rising or sinking fluid will tend to "overshoot" its equilibrium point due to its own momentum. The small vertical oscillations caused by this process of a fluid constantly overshooting its equilibrium point will, in turn, create large horizontal motions of the fluid, mostly along lines of gravitational potential. These g-modes are similar to waves on the ocean; even though the water is physically moving up-and-down, the waves travel horizontally toward the beach. These gravity-waves cause areas of different temperatures and densities to travel *around* the star. When the hemisphere of the star we happen to be looking at is locally hotter, it thus appears brighter, and vise versa. Thus, horizontally traveling gravity-waves cause time dependent changes, or pulsations, in the white dwarfs brightness. Figure 3 provides a depiction of the correlation of changes in surface brightness and observed flux for the DB star GD 358.

Pulsations in normal mass (~ 0.6 $M_\odot$) white dwarfs have observed periods ranging anywhere between 100 to 1500 seconds. There can be, and usually are, multiple g-modes present in white dwarfs. The propagation of each gravity-wave is determined by their wavelength and the star's interior structure. Thus pulsations can be used to probe stellar qualities such as interior temperature, cooling rates, interior composition, mass, rotation rate, magnetic-field strength, crystallization, etc. This process, known as seismology, is one of the few ways we can examine the interior or stars.

1.2. Binary Systems and Exoplanets

1.2.1. Characteristics of binary systems

It is estimated that roughly half the stars in the sky are binary systems, where two or more stars orbit a common center of mass. The study of binary systems, using relatively simple Newtonian physics, provides a great deal of information regarding their constituents. From Kepler's third law of motion,

$$P^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3 \tag{2}$$

we can obtain the sum of the masses ($M_1 + M_2$) provided that the period (P) and semi-major axis (a) are known. This sum can be combined with the simple geometric relation for ellipses

$$\frac{M_1}{M_2} = \frac{a_2}{a_1} \tag{3}$$

to obtain the individual masses. Corrections must be made for the proper motion of the system, yet this is relatively simple since the center of mass moves at a constant velocity across our line of sight (see Figure 4).

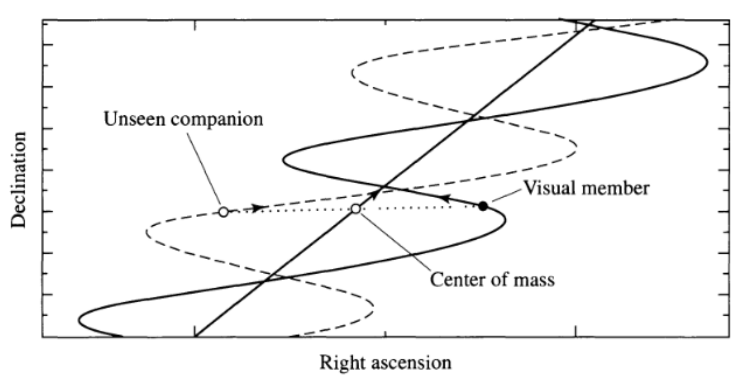


Fig. 4.—: The presence of an unseen companion can be implied by the oscillatory motion of the visible star. The proper motion of the center of mass moves with a uniform velocity (Carroll & Ostlie 2006)

Further corrections must be made due to the fact that the orbital plane may be tilted in relation to our line of sight. This information is often unknown or estimated and thus many binary properties are cited with a factor of sin(i) or cos(i) term, where i is the angle of inclination between the optical and binary planes. The inclination angle can be estimated by comparing the systems apparent center of mass with the observed elliptical orbit. Inclination can be much more accurately determined, however, if the system undergoes eclipses.

1.2.2. Eclipsing Systems

In order to observe an eclipsing system, where one star passes in front of its companion and blocks its light, the inclination i must be close to 90°. Unless the two stars are identical, one of the eclipses, called the primary eclipse, is likely to result in a greater decrease in brightness than the other, secondary eclipse. If the cooler, less bright star is much larger than the other, whereby 100% of the brighter star's light is blocked during primary eclipse, the measured flux of the system has nearly a constant minimum. By observing the secondary eclipse, where the smaller and brighter star passes in front of the larger, the minimum flux is not constant and can be used to determine i. As seen in Figure 5, the inclination of the system determines how long the smaller star takes to cross it's companion. One can then compare the two adjacent secondary eclipses to find i. One can also determine the radius of the smaller star by combining the measured velocities (obtained from spectroscopy) with the time between first contact and minimum light (t_a and t_b in Figure 5 respectively). Similarly, the radius of the larger star can be found with the time between first and last contact (t_a and t_b).

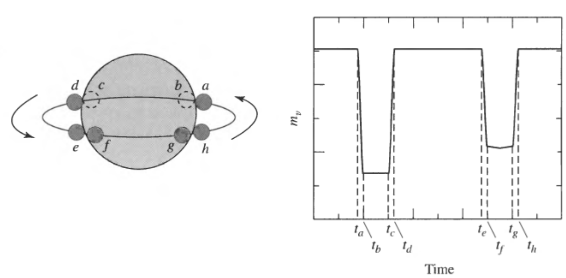


Fig. 5.—: The light curve for a secondary eclipse, showing that the system's inclination affects the time it takes the smaller companion to transit. (Carroll & Ostlie 2006)

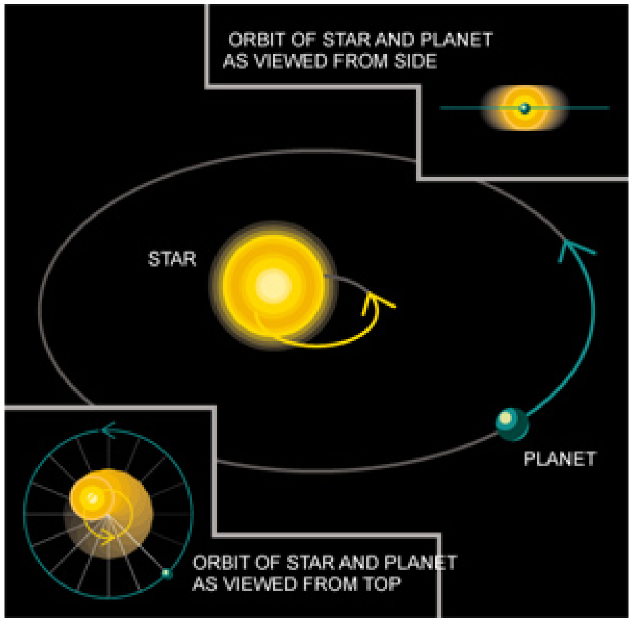


Fig. 6.—: The motion of a star around it's center of mass due to an orbiting planet. Image courtesy of Jared Schneidman Design

1.2.3. The search for exoplanets

As of March 2012, over 700 exoplanets have been found orbiting distant stars. The search for planets outside our solar system both helps constrain our current theories regarding solar system formation as well as raises possibilities for the evolution of alien life. Astronomers use both direct and indirect methods of finding exoplanets. Indirect methods do not detect planets explicitly, but rather rely on the wobble of the star during the planet's orbit. That is, both the planet and star move in elliptical orbits around a common center of mass (COM). While the COM is much closer to the star, due to its greater mass, there is still a small but detectable change it the star's position over time (see Figure 6). The radial velocity method of exoplanet detection, therefore, is to spectroscopically detect this stellar motion via the Doppler Effect. This method, however, heavily favors very massive planets because they cause a greater shift in the star's center of mass. An important direct method of exoplanet detection is the transit method, in which a planet crosses in front of a star and thus partially blocks its light. Similar to an eclipsing system, this produces a very slight minimum in the star's light curve. The Kepler spacecraft, launched in 2009, has used the transit method to detect over 200 confirmed planets and over 2000 planetary candidates (need reference). The transit method is heavily skewed towards large planets in close orbits.

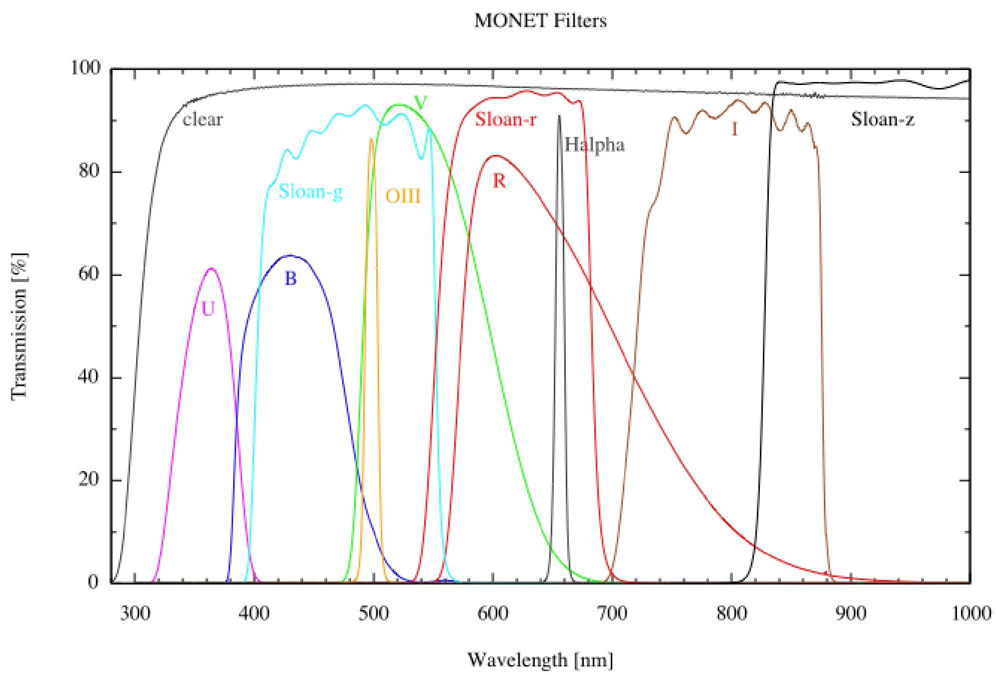


Fig. 7.—: Transmission curves for the available filters on the MONET telescope.

2. Using the MONET Telescope for Pulsating White Dwarf Studies

2.1. The MONET Telescope

The "MOnitoring NEtwork of Telescopes" (MONET) consists of two 1.2-m remotely operated imaging telescopes. The first telescope (MONET North) is located at the McDonald Observatory in West Texas and became operational in 2006. The second telescope (MONET South) is located at the South African Astronomical Observatory and is currently in the final stages of construction. The telescopes were funded by the Alfried Krupp von Bohlen und Halbach Foundation and the Georg-August-Universität Göttingen. The alt-az mounted f/7 RC design was chosen to permit good sampling of the expected $\sim$ 1" seeing as well as fast movement and operation. The MONET was originally designed to observe photometric variables such as cataclysmic variables, young stars, AGNs, etc. This, therefore, makes the MONET optimal for observing pulsating white dwarf studies.

The MONET North is equipped with a 1.20-m primary and 0.50-m secondary mirror with a 8.40-m focal length. The CCD is located at Nasmyth focus with a plate-scale of 24.56 arcsec/mm. The 1024x1024 CCD contains 0.32 arcsec/pixel, creating a 5.46 arcmin field of view. The telescope is equipped with twelve 70 mm square filters whose properties can be seen in Figure 7 and Table 1.

Table 1. Available Filters for the MONET Telescope

Filter Name	Description	Central Wavelength (nm)	FWHM (nm)	Peak Wavelength (nm)	T_{max} (%)
none	no filter	(CCD)	(CCD)	(CCD)	(CCD)
clear	BG glass	(CCD)	(CCD)	(CCD)	0.97
U	Johnson-Bessel uv	360	51	364	0.62
B	Johnson-Bessel blue	440	94	431	0.66
V	Johnson-Bessel visual	550	109	520	0.93
R	Johnson-Bessel red	660	142	600	0.83
I	Johnson-Bessel infrared	800	156	805	0.94
Sloan g'	SDSS green	475	150	492	0.96
Sloan r'	SDSS red	619	132	629	0
Halpha	neutral hydrogen	655.8/656.2	8.2	656	0
OIII	twice ionized oxygen	498.20/498.90	11.60/11.80	500	0.87
Sloan z'	SDSS near-IR	$\geq$ 900			0.95

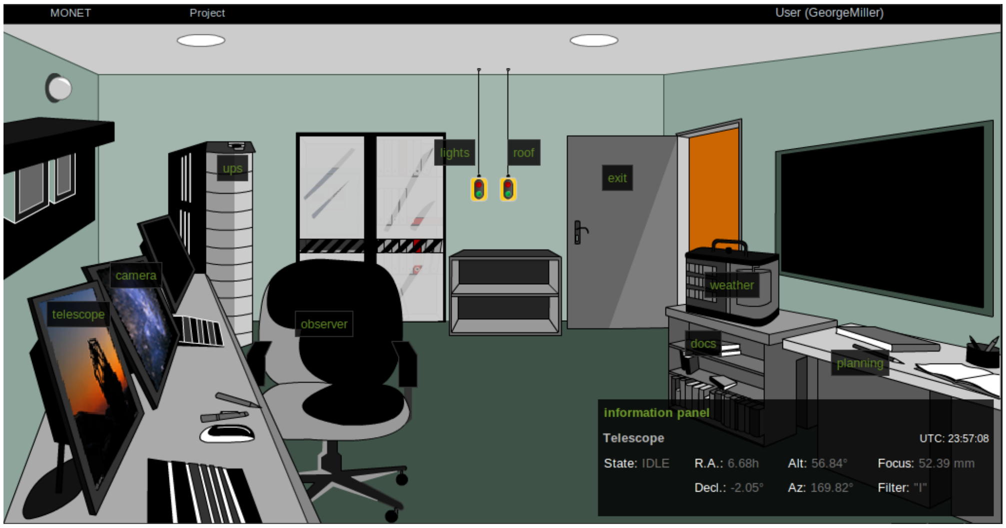


Fig. 8.—: The initial user interface for the MONET Telescope. Anyone has access to this window and can check the telescope's position, focus, exposure time, etc. as well as the weather and roof.

While the MONET telescope can be operated remotely using multiple VNC connections which give the operator access to the computers controlling the telescope, most users use a browser based user interface which mimics a physical control room. Various screen shots of the user interface can be seen in Figures 8 and 9.

2.2. A Handbook on Using the MONET for Time-Series Photometry

Performing time-series photometry with the MONET is relatively simple, although the data reduction process can be complex. In the following section, I will first explain how to use the MONET specifically for taking time-series data. Much of this relies on my first-hand experience. Secondly, I will explain how to reduce the data from scratch. This section is intended primarily as a manual and may be skipped over by the more casual reader.

2.2.1. Observing pulsating white dwarfs with the MONET

The following is *not* intended as an all-purpose manual for observing with the MONET telescope. Rather, it is a collection of my own personal experiences using the MONET telescope to obtain time-series data of white dwarf stars. For a more complete manual on the MONET telescope, please reference *An Introduction to Astronomical Image Processing*

Fig. 9.—: The main telescope user interface where the telescope and camera are operated. The telescope's position and status can be found in the left-most panel. The camera is controlled from the bottom panel. Exposure mode options are Normal, Dark and Bias. 1x1, 2x2 and 4x4 binning are available, but 2x2 binning should always be used for time series photometry. The telescope is operated from the right-most panel.

with ImageJ by Dr. Frederic V. Hessman and Dr. Eckart Modrow.[1]

1. To begin, observing with the MONET telescope is a time-demanding process. Ensure that you are free from sunset-McDonald time (if you are observing first) until the remainder of your alloted time. Observing with a remotely operated telescope should not be taken lightly; it is unpredictable what serious problems may occur that will require your attention. Various contact information for assistance can be found in the MONET portal, but if ever in doubt always close the roof doors and turn off the telescope (if you feel this won't cause additional damage) before continuing. You should never leave the telescope unmanned while the roof doors are open.

2. If you have telescope time at the beginning of the night, you will need to take twilight flats. A flat-field attempts to measure both the pixel-to-pixel sensitivity across the CCD as well as correct for possible obstructions in the optical path such as dust. Twilight flats attempt to expose the entire CCD chip to a uniform amount of radiation, and

[1]This text can be found online at http://www.astro.physik.uni-goettingen.de/ hessman/ImageJ/Book

thus must be taken when the sky is bright enough to be uniformly lit (aka brighter than most stars) but not so bright as to damage the CCD. Generally, in my experience with the MONET, this occurs roughly 20-30 minutes after sunset. Flats should be taken with the same filter you intend to use for the night. If you are unable to obtain twilight flats for that night, you may use a previous night's flat field, although this is not ideal.

3. One should always attempt to take bias and dark-fields for each run. You must always open the dome before initializing the telescope, so ensure that it is sufficiently dark outside to avoid outside light entering your dark-fields. Darks should always be taken with the same exposure times you intend to observe with. All calibrations should also be taken with the same binning you intend to use in your observations. If you end up observing with a different exposure time than you expected, you should take these dark calibrations at the end of your run. Again, you may use the calibration fields from a previous night but this is not ideal.

4. For any string of images you wish to reduce at a later point (calibrations or object images) you should record the exact UTC times of the first and last images in your observing log. This time can be found directly in the image name, i.e. for the image "*McD_2012-04-24T03-21-10_Nclear.fits*" one should record "03-21-10" in your log. The reason for this is simply for convenience's sake and will become apparent when reducing your data.

5. I have taken most of my white dwarf data on the MONET using the *clear* filter. While most larger telescopes tend to use blue filters when observing white dwarfs, I have found it optimal to collect the most flux possible given the limitations of a smaller telescope.

6. Use 2x2 binning when taking time-series photometry. This had two chief advantages: 2x2 binning has the shortest readout time between exposures and the CCD is also more sensitive.

7. The determination of which exposure times to use should be made on a night-by-night basis. I generally only recommend using 5-second exposures when observing a bright star under very clear weather, with little danger of the conditions worsening. I recommend using 10-second exposures for 14th-15th magnitude stars, 15-seconds for 16th-17th magnitude stars and 30-seconds for any higher.

8. When setting up the star-field you intend to observe, you should attempt to include as many bright comparison stars as possible. However, ensure that these stars are not

so bright as to damage the CCD. If the chip looks saturated around a bright star, you should move it off your field of view. Also, remember that automatic tracking is not perfect and the stars will tend to drift throughout the run. The target star should therefore not be placed near the edges of the chip. In general, the field of view will drift the most when the telescope is closest to zenith. It is possible to stop a run and reposition your field, but this is a hassle you should attempt to avoid.

9. The orientation of the CCD will not always be the same as your reference finder chart. You may use ImageJ to rotate or flip your images to correct for this, however it is often easiest to just tilt your neck.

10. While a long run is in progress, the temptation to multi-task elsewhere will be strong. Always plan on checking the telescope and weather at least every few minutes to ensure everything is in working order. Personally, I use a separate monitor which always displays the telescope portal and weather conditions. You should also periodically download your images and make sure your stars have not drifted too far and you are still in focus.

11. Make your observing log as detailed as possible. I recommend also keeping a paper log in case the online observing log malfunctions. A well kept log-book will not only make reducing the data far easier, but will ensure the validity of your data.

2.2.2. Reducing MONET data

Much of the reduction process I have written is scripted to be more user-friendly. A more detailed explanation will follow if the reader finds him/herself needing to continue mid-script. These scripts assume you are using the University of Texas computer *rocky* where various reduction tools are located. For use on other computers, email me or any other member of the UT White Dwarfs group to obtain the necessary scripts. This program uses the MATLAB oriented MAESTRO code written by James Dalessio and specialized for pulsating white dwarfs (Dalessio 2010). You may download this program from *wholeearthtelescope.org*. To reduce MONET data:

1. Navigate to the directory where your MONET data is stored or you wish your MONET data to be stored. For *rocky* this is located in the directory */data4/rocky/smaug/monet.*

2. Type *mreduce*

3. Enter the year, month and days in which the observation was taken. The days will span the evening and morning of the observation and should be entered in the form *06-07*. This may take several minutes as data is being copied from the *alfred* computer.

4. Enter the UT times of your first and last bias, dark, flat and object images. These should be written down in the log from your observations. If they are not, you will need to consult the list of images which can be found in the MONET wiki. The times will need to be entered in the form *00-23-32* as they are written in the image names.

   (a) Enter *none* if you do not wish to use that specific calibration. If you wish to use the calibration images taken from a different night, enter *other*. You must then enter the directory where these fits files are located. They should be isolated from all other images.

   (b) If your object images are split into multiple sequences, the script will prompt you to enter the UT times of each of these strings. Type "*n*" when prompted if you have listed all your images.

5. After several minutes, the MAESTRO package will begin. Depending on the length of your run, this may take anywhere from 15 minutes to an hour to finish. Once the script exits, it will give specific instructions on what to do next.

6. You must now denote which star is your target (i.e. the one you wish to produce a light-curve of).

   (a) As the script exited, it gave the location of the field file you need to edit. For example, it may tell you "*Now please edit the file /home/rocky/ccd/.Maestro/fields/2010.12.06-07*. This can be done using any text editor such as vim or emacs. The file should contain four columns "name, x, y, amplitude.

   (b) The image the fields file is references is listed at the top. Locate this image in the *Objects* directory where you data is now located.

   (c) Use ds9 to open this image. Consult a finder-chart as to which star is your target. Scroll your mouse over this star and write down the x-y coordinates of this star, which can be found at the top of the ds9 window. *Note: the image may be rotated in comparison to your finder chart.*

   (d) Locate these target coordinates in the fields file you are editing and move this line to the top. You no not need to change the numerical naming of the lines (i.e. unknown1, unknown2, unknown3, ...). Also, move any comparison stars you wish to use into the second, third and fourth positions.

7. Navigate to the *lists* directory where your data is located. As the previous script exited, it tells you where this directory can be found.

8. As the script exited it also told you what command to enter next. This command should begin with *maestro*. For example, *maestro -c monet reduce -s 2010.12.06-07*. Maestro will now run again and perform the necessary aperture photometry. Depending on the length of your run, this may take anywhere from 15 minutes to several hours.

9. Once MAESTRO is complete, it will create a directory with a very long name. Use the "mv" command to change this name if you like, and then cd into it.

10. Type "*m_chooselc counts_*" to physically examine each aperture. Once you have selected the aperture which shows the least scatter, type "q" and enter this into the terminal.

11. A file called *firstimage.fits.wq* should have been created. Open this with a text editor and edit the "Object" field. If the star has never been reduced before, you will need to enter the coordinates into the file "*/home/rocky/ccd/.wet/stars.dat*.

12. Copy a file called "seconds" from the Objects directory. This can be done by typing "*cp ../../Objects/seconds .*"

13. Type *wqfix firstimage.fits.wq* This should create a file called monet.wq

14. Your data is now ready for the Wqed data reduction program.

    (a) Start wqed by typing wqed monet.wq. A window should pop up showing you the lightcurve. The white dots are the target star.

    (b) Select the target star by typing [1]. Remove obviously bad points by typing [g] (for garbage) and selecting the region to delete. You may also select which regions to keep, garbaging any data outside of it, by typing [CTRL]+[G]. If you are unhappy with your choice hit [CTRL]+[U] to undo.

    (c) Hit [/] and divide the target lightcurve by one or more reference stars by selecting the appropriate numbers.

    (d) Fit a second order polynomial to the divided lightcurve by typing [f] then [2].

    (e) Save your reduction by typing [w], then [e].

    (f) Type [q] at any time to quit.

15. To create an FT of your output, type fitlc monet.lc1

2.3. MONET Observation Results

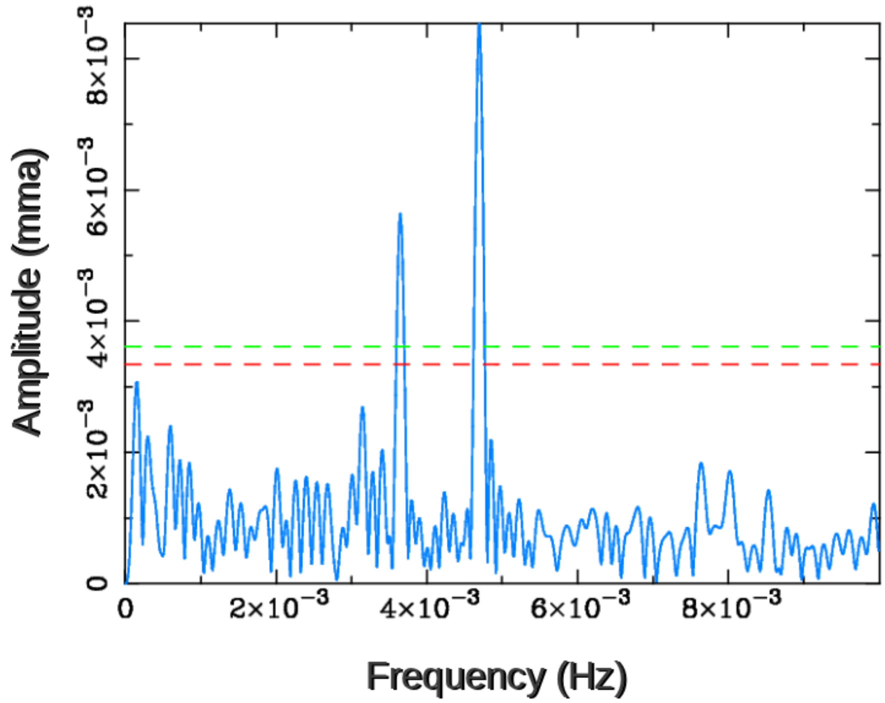
Below I have produced the Fourier Transforms (FTs) for various pulsating white dwarf stars taken with the MONET and reduced with the MAESTRO aperture reduction routine. For comparison, I also include FTs of the same star taken with the 82" Otto Struve Telescope at McDonald Observatory. I have attempted to choose runs of similar length and weather conditions for an accurate comparison. The primary frequency modes are also listed for each star. The red and green lines represent the 99% and 99.9% false alarm probabilities respectively. In general, the noise amplitude is roughly twice as high for MONET data than the 82", as it to be expected for a smaller telescope.

R548 (Figure 10) is a comparatively bright (14.1 mag) DAV white dwarf. Mukadam et al. 2003 showed that the 213 second period drifts at a very slow rate of $dP/dt \leq (5.5 \pm 1.9) \times 10^{-15}\,\mathrm{s\,s^{-1}}$, making R548 a good test for the MONET timing accuracy (see section 2.4.1). As seen in Table 2, the measured period on the MONET and 82" telescopes match almost entirely, confirming that the MONET reductions are in fact accurate.

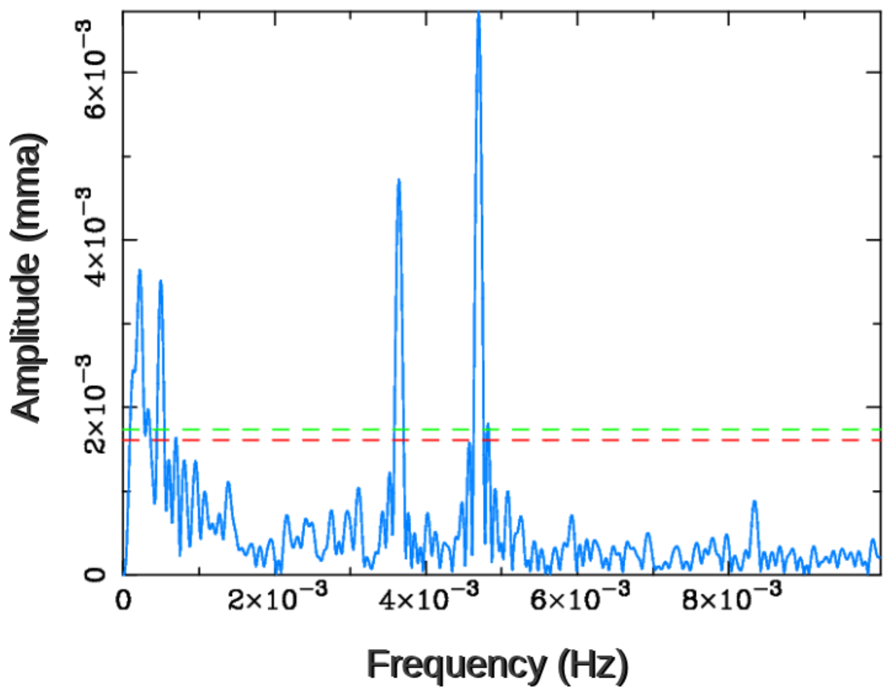
GD66 (Figure 11 is a 15.6 magnitude DAV white dwarf with a surface temperature of 11980K. As is discussed in Section 2.4.1, GD66 should show very stable pulsation periods similar to R548. The possibility of orbiting bodies, however, may contribute to their instability (Mullally et al. 2008). Therefore, one cannot directly compare the periods of GD66 taken at times to determine timing accuracy. We can clearly see from the Fourier Transforms, however, that the two primary periods can easily be resolved with the MONET telescope.

Table 2. Measured periods and amplitudes for R548

R548			
14.1 (v) Apparent Magnitude			
MONET Telescope		82" Telescope	
Period (sec)	Amplitude (mma)	Period (sec)	Amplitude (mma)
213.01±0.18	0.00855±0.00059	212.988±0.075	0.00672±0.00023
274.29±0.43	0.00571±0.00057	274.600±0.190	0.00473±0.00025

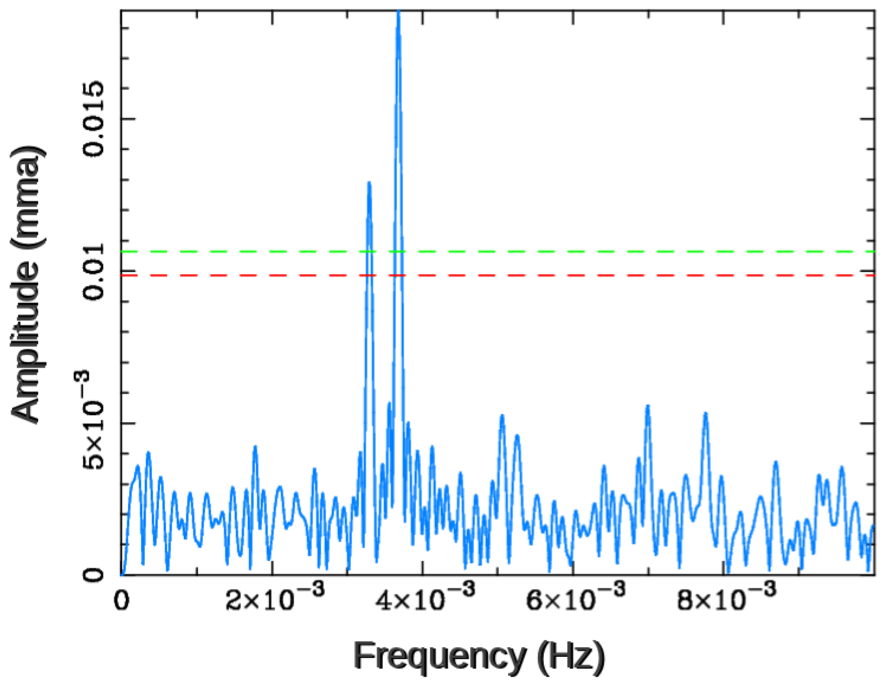


(a) MONET Telescope

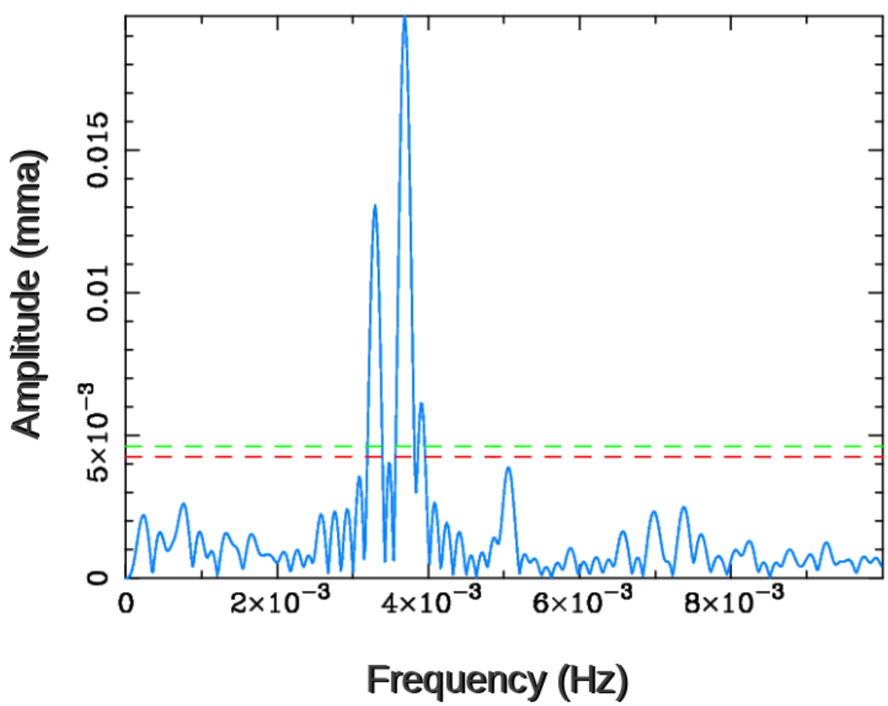


(b) 82“ Telescope

Fig. 10.—: R548



(a) MONET Telescope



(b) 82“ Telescope

Fig. 11.—: GD66

2.4. Possible Applications of MONET Time-Series Data

2.4.1. A study of long term periodic variability of DAV periods

The change of a pulsating white dwarf's period over time can be characterized by a star's $\dot{P}$, or dP/dt. DAV white dwarfs near the hot end of the instability strip (hDAVs) have been observed to have extraordinary stability in their periods of pulsation and thus very small $\dot{P}$s (Stover et al. 1980). For example, Kepler et al. 2005 measured a $\dot{P}$ for the hDAV G117-B15A of $3.57 \pm 0.82 \times 10^{-15}\,\mathrm{s\,s^{-1}}$, while Mukadam et al. 2003 constrained R548, another hDAV, to a $\dot{P} \leq (5.5 \pm 1.9) \times 10^{-15}\,\mathrm{s\,s^{-1}}$. Some of these hDAVs which should theoretically display stable periods, however, show long term periodic variability in their pulsation periods.

One explanation for this periodic signal in a star's $\dot{P}$ is the presence of planets orbiting the white dwarf. As the planet causes its host star to wobble around its center of mass, the pulsations reach earth earlier, and then later than expected in a periodic manner. The very first exoplanets were discovered around pulsar PSR1257+12 using this very mechanism (Wolszczan & Frail 1992). Mullally et al. 2008 identified 15 candidate hDAV stars to search for such periodic changes in pulsation periods as evidence for orbiting planets. To display these results, we utilize an O-C ("Observed minus Calculated) diagram, which displays the departure of the observed time of events (measured periods in our case) from their expected values. For a DAV, we expect

$$O - C = \Delta E_0 + \Delta P E + \frac{1}{2} P \dot{P} E^2 \tag{4}$$

where E is the time of each event, ΔE_0 is an arbitrary start time and $\Delta P = P - P_1$ the deviation from a constant period P_1. To account for an orbiting body, we simply add on a $Asin(\frac{2\pi}{\Pi} t + \phi)$ term, where Π is the orbiting body's period.

Table 3. Measured periods and amplitudes for GD66

GD66			
15.6 (v) Apparent Magnitude			
MONET Telescope		82" Telescope	
Period (sec)	Amplitude (mma)	Period (sec)	Amplitude (mma)
271.90±0.32	0.0186±0.00179	271.28±0.16	0.01967±0.00049
303.65±0.60	0.0130±0.00180	303.63±0.41	0.01309±0.00065

Of the 15 hDAVs being observed for possible orbiting planets, WD1354+0108 and GD66 have shown the most promise. WD1354 is a relatively low amplitude DAV which is dominated by two primary frequencies at 198.3 and 291.6 seconds. Figure 12 displays the O-C for each of these frequencies as well as the best sinusoidal fit corresponding to an orbital period of 4.6 years. This sinusoid, however, is only marginally better than a straight line fit and more data is needed before we are confident that the signal is real. The 15.6 magnitude DAV GD66 is a higher amplitude pulsator which allows for smaller error bars in its O-C points. The Fourier transform for GD66 using both the MONET and 82" telescope is shown in Figure 11. The O-C for the 302 second period in GD66 (see Figure 13 shows a high amplitude signal corresponding to a 4.0 year period orbiting planet. The 272 second period also displays a similar periodic signal of 3.9 years. When compared together, however, the two sinusoids are almost exactly out of phase with each other. This effect rules out planets as a possible explanation, for the light-travel effect caused by orbiting planets should cause all pulsation modes to vary with identical time-scale and phases. There are currently no well-established theories as to what could cause these two large, out-of-phase sinusoidal signals. Such processes could be completely unknown among white dwarf astronomers and provide ground-breaking insight into stellar pulsations. More data, preferably obtained every new moon cycle, would help constrain the exact shape of this periodic trend and potentially lead to an explanation. The MONET telescope is ideal for this project, as time can be obtained at very regular intervals over multiple years. Figure 11 shows that the telescope is sensitive enough to pick out the two main frequencies present in GD66. Continued observations of GD66, WD1354+0108 and other hDAV stars, most of which are bright enough for a 1.2m telescope, has the potential for both finding new planets and discovering new pulsation processes and is therefore a perfect project for future MONET users.

2.4.2. Extremely low mass pulsators

All previously found ZZ Ceti pulsating white dwarfs have fallen within masses of $0.5 - 1.1 M_{\odot}$. These stars have C/O cores and are likely formed through standard single star red-giant evolution. The instability strip of these pulsators has been extremely well constrained (Mukadam et al. 2006, Gianninas et al. 2007) and the theoretical understanding of the pulsations has been very precisely developed (Winget & Kepler 2008). Pulsations in stars $\lesssim 5 M_{\odot}$ have been predicted, however, and searched for (Steinfadt et al. 2012). These extremely low mass white dwarfs (ELMs) are believed to form through binary star evolution, where mass transfer can prevent the ignition of He into C/O in the core, yet this process is not well understood. The discovery of pulsations within ELMs would allow for asteroseismology to probe into their depths and extract crucial structural information necessary for formation

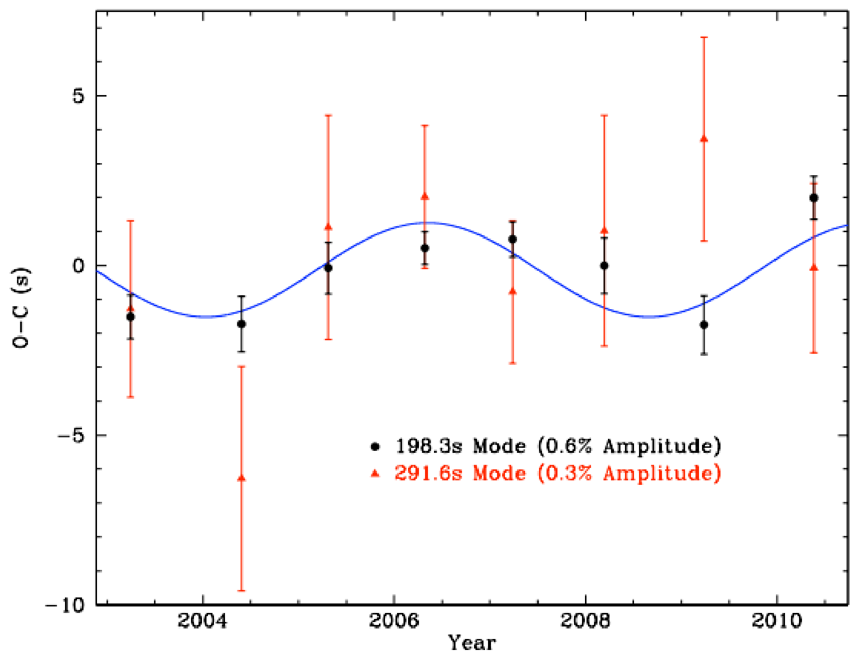


Fig. 12.—: O-C for WD1354+0108, a 16.4 magnitude hot DAV.

scenarios.

In April 2012, Hermes et al. 2012 confirmed the existence of the very first pulsating ELM white dwarf SDSS J184037.78+642312.3. This star has a T_{eff} = 9100 ± 170 K and a log g = 6.22 ± 0.06, which corresponds to a mass of ∼0.17 $M_{\odot}$. J1840 shows high amplitude pulsations peaking around 4000 seconds, far higher than the known C/O core ZZ Cetis. To observe this 18.8 magnitude white dwarf on the MONET telescope would require near perfect weather conditions and 30 second to 1 minute exposure times. Given the long pulsation periods, however, such long exposures should adequately sample the data in order to resolve the primary pulsations. A more promising prospect for the MONET telescope, however, is an extensive search for more of its ELM pulsating brethren. The ease of access and availability of the MONET telescope will allow for the long and consecutive time-series data necessary to discover such low frequency pulsations. Several brighter low mass white dwarfs have already been identified for such a search, and should be observed within a year. This process will likely involve welding together multiple 4-5 hour observing runs, preferably taken on consecutive nights. The exploration of these ELM pulsators will provide exciting insights into binary system evolution as well as pulsation theory within He rich environments.

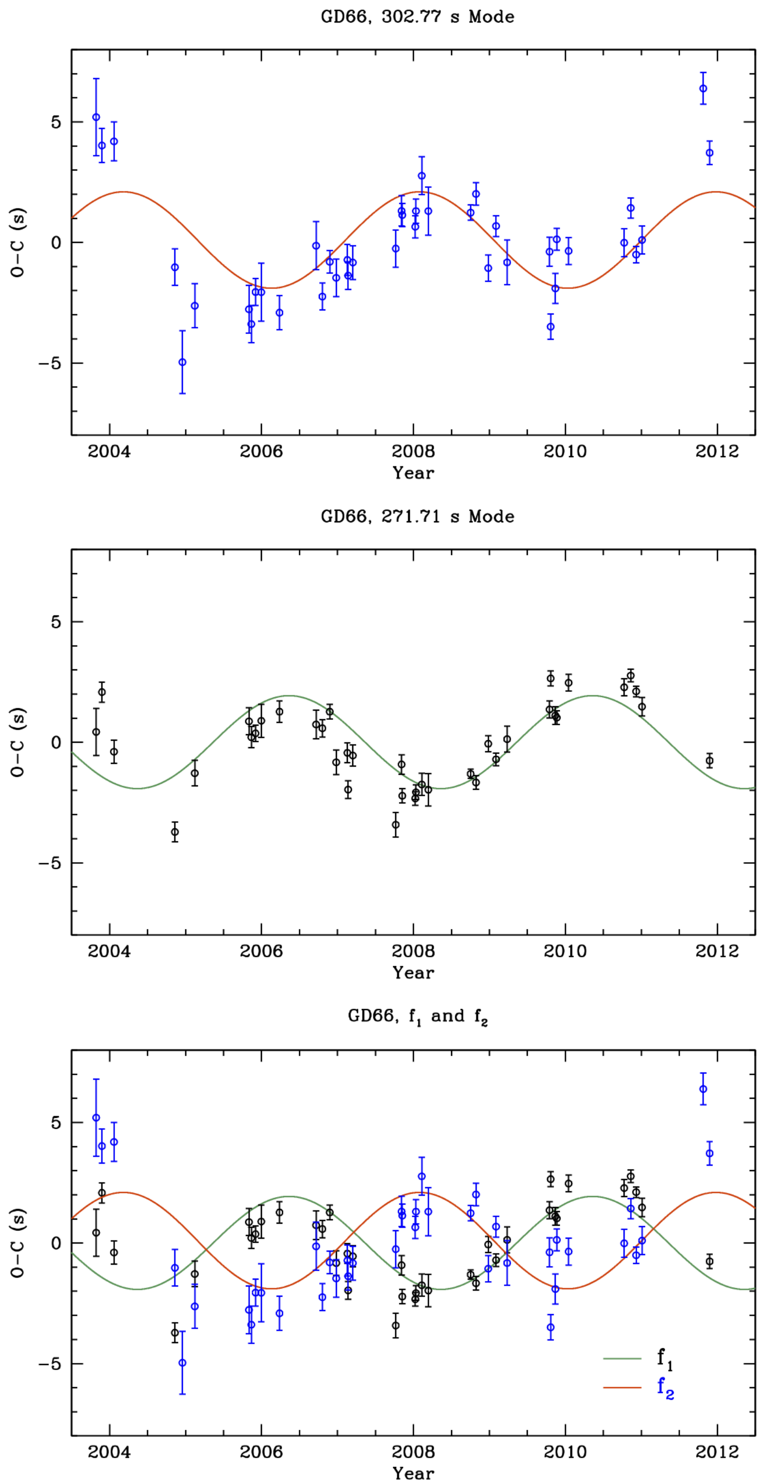


Fig. 13.—: O-C for the two dominant pulsation periods of GD66, a 15.6 magnitude DAV. When plotted on top of each other, we can see that the two signals are almost directly out of phase. Figures courtesy of JJ Hermes.

2.5. Discussion

Using the MONET telescope to obtain time-series data has a number of advantages: 1) Time-sensitive data can be obtained quickly without having to wait for observing proposals to be accepted. 2) Data may be obtained evenly throughout the year, which is crucially important for studying long term variability such as in hDAVs. 3) The MONET can be used as a guinea pig to observe stars and therefore prevent wasting costly large-telescope time. 4) No travel funds are necessary and observing can be enjoyed from the comfort of your own home! It is my hope, now that I have shown the MONET can be used to study pulsating white dwarfs as well as developed an image reduction pipeline for its data, that future students will take advantage of this wonderful opportunity afforded to them. In particular, the MONET is a perfect tool to allow newly entering pulsating white dwarf students to begin research.

3. The Discovery of Two Planets Orbiting the Eclipsing System NN Serpentis

3.1. Introduction

To date, over 700 exoplanets have been found orbiting distant stars. In just a decade, the age-old question of our own Earths uniqueness has exploded into one of the most exciting and fastest-growing subjects in modern astronomy. Most of these 700 exoplanets, however, orbit single, main sequence stars similar to our own sun. This is largely due to observational bias, since these stars are best suited for the popular radial-velocity method of planet detection. Planets orbiting close binary systems are in principle very hard to detect. Classical approaches of radial velocities cannot be used for a number of reasons. For one, binary systems are in general more massive than a single star of the same magnitude and thus are closer to the center of mass. Furthermore, short-period planetary orbits (which radial velocity methods are most sensitive to) are unstable around binaries (Muterspaugh et al. 2010). Finally, it is often not possible to obtain two separate specra of the binary components, and the presence of two sets of spectral lines can complicate measurements. The presence of circumbinary planets (planets which orbit both stars rather than just one) are even rarer, and before the discovery of planets orbiting HW Vir and NN Ser had never been found (Lee et al. 2009). Yet perhaps the most extraordinary form of exoplanets are those orbiting evolved stellar systems, such as the white dwarf in NN Serpentis.

NN Serpentis is a short period detached eclipsing binary containing a hot DA white dwarf and a much cooler M4 dwarf star with masses .535 $M_\odot$ and .111 $M_\odot$ respectively. Such close binaries such as NN Ser result when the more massive star evolves into a red giant and engulfs the orbit of its companion. This common envelope (CE) causes the red giant's mass to be cast off in a planetary nebula (leaving behind a subsequent WD) as well substantially shortens the binary period. Furthermore, the period of this post-CE system will continue to shrink due to loss of angular momentum from stellar winds until they come into contact and form a cataclysmic variable (CV).

A number of eclipsing post-CE systems show long-term, sinusoidal variations in their mid-eclipse ephemerides, such as V471 Tau (Kamiński et al. 2007), HW Vir (Lee et al. 2009), HU Aqr (Schwarz et al. 2009), QS Vir and NN Ser (Parsons et al. 2010) and DP Leo (Qian et al. 2010) (Beuermann et al. 2011). Of these, NN Ser provides deep and well defined eclipses, allowing mid-eclipse time measurements with an accuracy of 100 ms or better (Brinkworth et al. 2006). Furthermore, NN Ser is comparatively simple, with little accretion or magnetic field effects from the white dwarf. The system thus yields itself to an in-depth analysis of the cause(s) of these observed period variations. Possible explanations often put forth include Applegate's mechanism, apsidal motion and the presence of a third body orbiting the system. Through an analysis of mid-eclipse observations on both long and short time-lines, we can place constraints on the validity of these processes and rule out all explanations but that of additional bodies orbiting the system.

3.2. History of Observations and Analysis

Following the initial discovery of NN Serpentis eclipses in 1989, Haefner et al. 2004 procured a series of accurate eclipse times with the ESO 3.6m telescope equipped with the MCCP photometer. Ten years later, they obtained a potentially very accurate VLT 8.2m trailed image, whereby the the star is trailed along columns of the CCD using precise tracking rates and column alignments (Haefner et al. 2004). This trailed image was reanalyzed by Beuermann et al. 2010 using a different conversion of the track from pixel space to time to revise the mid-eclipse time error from 17s to 0.20s. This reanalysis was key, for it provided a highly accurate data point on which to compare later observations. Since 2002, the Warwick group have used the WHT+UltraCam to obtain 22 published mid-eclipse times with errors ranging from 0.02 to .35 seconds (Brinkworth et al. 2006), (Parsons et al. 2010). In 2010, using new 2.4m data from the Yunnan Observatory, Qian et al. 2009 proposed a third body orbiting the system with a mass $M\sin(i)=0.0107\pm0.0017\ M_{\odot}$. These orbital parameters, however, were shown incompatible with new data taken by Parsons et al. 2010 (see Figure 14).

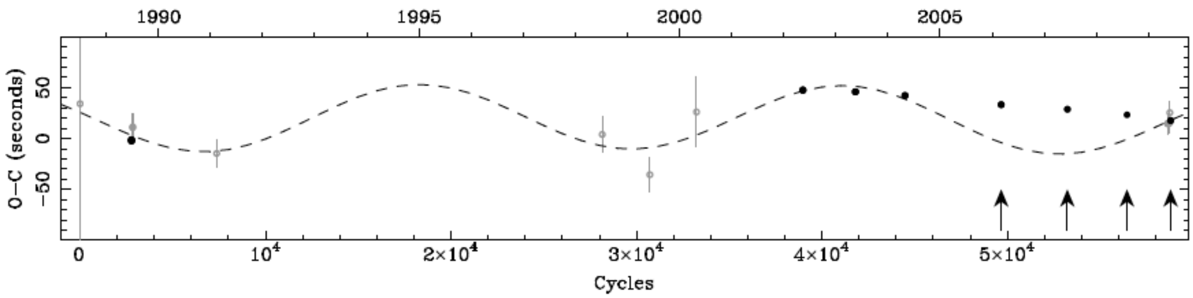


Fig. 14.—: OC diagram for NN Ser based on the ephemeris of Brinkworth et al. 2006, with sinusoidal fit from Qian et al. 2009 over plotted. The additional ULTRACAM points from Parsons et al. 2010, indicated by the arrows, clearly disagree with the fit. Figure provided by Parsons et al. 2010

3.3. New Observations

Up to 2009, observations of NN Ser were separated by around a year. Short term variations of mid-eclipse times, an integral facet to constraining the fits of N body simulations, were therefore lacking. An international collaboration was therefore started between the University of Göttingen, the University of Texas at Austin and the University of Warwick to continuously monitor NN Ser throughout 2010. My role was to observe eclipses of NN Ser using the 2.1m Otto-Struve and 1.2m MONET telescope at McDonald Observatory and help coordinate timing information between my German and UK counterparts. Data on the 2.1m was taken with a BG40 filter using the Argos high-speed photometric camera. The prime-focus location, frame transfer duel CCD layers and GPS synchronized pulse triggers makes Argos highly efficient for taking time-series data (Mukadam & Nather 2005). In order to correctly fit a trapezoidal shape to eclipse data, a flat base line when the system is out of eclipse is needed, as well as straight ingress and egress eclipse lines. The Quilt image reduction software's use of comparison stars to correct for atmospheric extinction and weather conditions thus also makes the 2.1m especially useful for accurate eclipse data. At any point in time, the measured fluxes of stars can vary due to incoming clouds or turbulence from atmospheric processes. By dividing by comparison stars in the field which should maintain a constant flux, however, these effects can be removed. A screenshot of the data acquisition software can be seen in Figure 15, where NN Ser is circled in blue and comparison stars in red.

An eclipse of length τ is modeled by a trapezoidal light curve with maximum flux F_0 and minimum $F_0(1 - \frac{h}{2})$ where h is a dimensionless positive number producing an eclipse of depth $\frac{hF_0}{2}$. In the case of NN Ser, where the secondary is very faint, h is about twice the

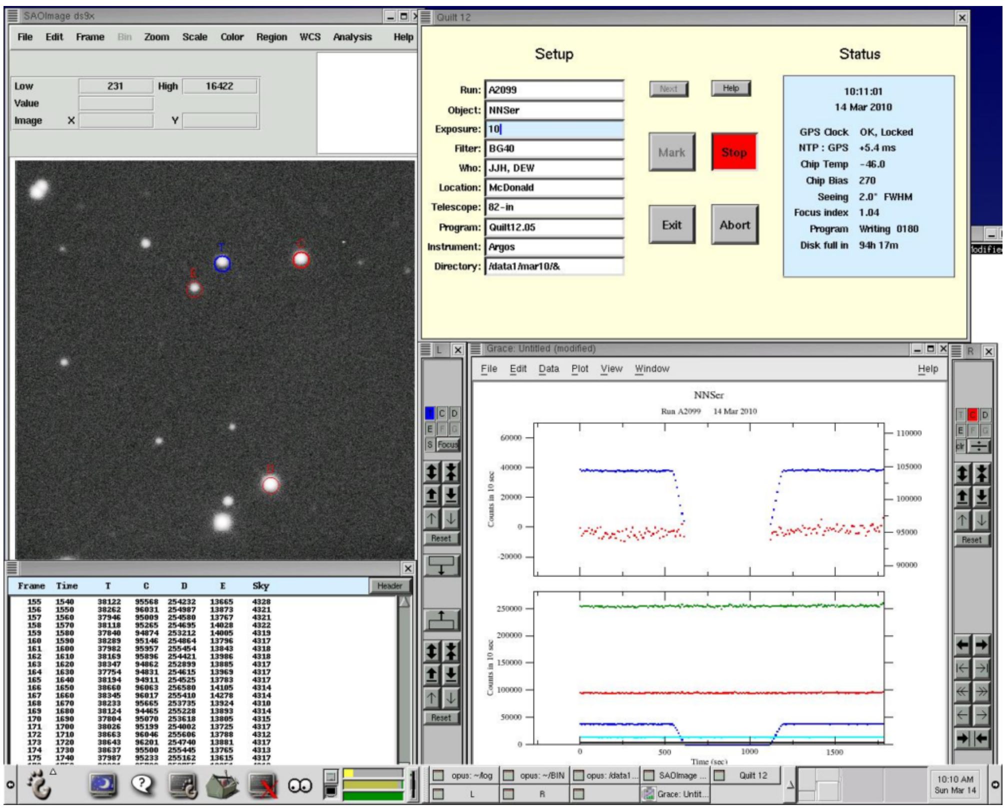


Fig. 15.—: Screen shot of NN Ser eclipse taken with Argos and using the Quilt software. A real-time image of the field can be seen in the top-left, with NN Ser circled in blue and the comparison stars in red. The measured photon counts for each star is present in the bottom-left. A plot of the eclipse data, once divided by the comparison stars, can be seen in the bottom-right.

ratio of the squares of the stellar radii. The functional form of the trapezoid is therefore given by,

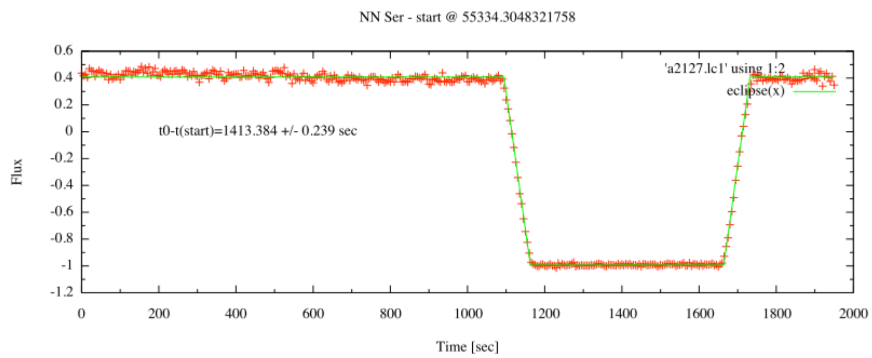
$$F(t-t_0) = \begin{cases} F_0 & t-t_0 \le -\frac{\tau}{2} \\ F_0(1-\frac{ht}{kt}-\frac{h}{2k}) & -\frac{\tau}{2} \le t-t_0 \le -\frac{\tau}{2}+\frac{k\tau}{2} \\ F_0(1-\frac{h}{2}) & -\frac{\tau}{2}+\frac{k\tau}{2} \le t-t_0 \le \frac{\tau}{2}-\frac{k\tau}{2} \\ F_0(1+\frac{ht}{kt}-\frac{h}{2k}) & \frac{\tau}{2}-\frac{k\tau}{2} \le t-t_0 \le \frac{\tau}{2} \\ F_0 & \frac{\tau}{2} \le t-t_0 \end{cases} \tag{5}$$

where $k \approx \frac{2R_2}{R_1+R_2}$ (Muterspaugh et al. 2010). A total of six eclipses were taken using the 2.1m at McDonald Observatory. Three sample trapezoidal fits can be seen in Figure 16. Seven further eclipses were obtained using the remotely operable 1.2m MONET/North telescope using white light by myself and others, and two additional eclipses from the ESO NTT 3.5-m ULTRACAM using Sloan g photometry.

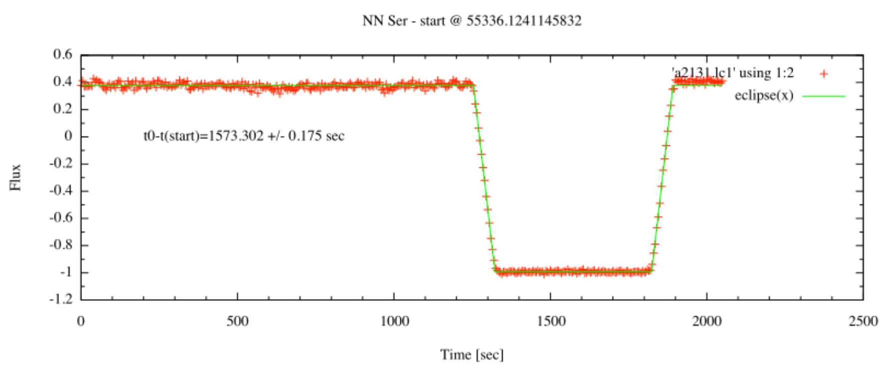
3.4. Possible Explanations for Eclipse-Time Variations

Possible explanations for timing variations in eclipsing systems are Applegate's mechanism, apsidal motion, and the light-travel effect of other bodies orbiting the system. In 1992, Applegate proposed magnetic activity cycles within low-mass companions in eclipsing systems can redistribute the angular momentum within the star's interior (Applegate 1992). This effect would change the stellar quadrupole moment and thus change the orbital period of the system. Lanza et al. 1998 later proposed that this mechanism could also be driven by a conversion between rotational kinetic energy and magnetic energy. While it is assumed that the Applegate mechanism occurs in most, if not all binaries, in the case of NN Ser the observed variations of $\sim$ 20 seconds are far too large for this mechanism to be the cause. That is, the required energies are much larger than the total radiant energy of the M4 component (Brinkworth et al. 2006).

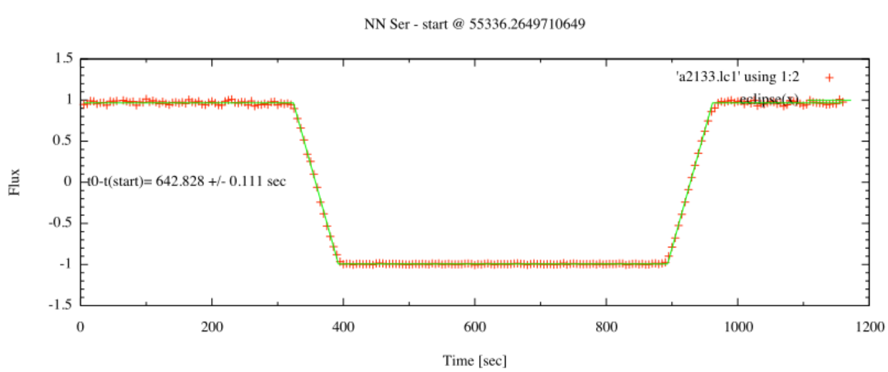
Apsidal motion, the precession of the periastron in the orbital plane caused by tidal gravitational moments, is also known to produce orbital period changes in binaries. However, apsidal motion would also produce variations in the full width half maximum (FWHM) of the eclipse as well as time shifts in the secondary eclipse, neither of which is observed in NN Ser. Furthermore, NN Ser deviates from the nearly uniform sinusoidal signal apsidal motion would create (see Figure 18). Thus, the presence of additional bodies orbiting the system remains the only explanation for NN Ser's long term timing variations.



(a) Run A2127



(b) Run A2131



(c) Run A2133

Fig. 16.—: The trapezoidal fits to eclipses taken using the 2.1m. Run A2127 was taken on May 18 2010 and runs A2131 and A2133 were taken on May 20 2010.

3.5. Analysis

Additional bodies orbiting the eclipsing system will cause the binary to wobble back and forth along our line of sight. This movement will cause the eclipses to sometimes appear closer to us (and thus arrive sooner) and sometimes farther away (and thus arrive later). Models of this light-travel effect caused by k planets in a binary system is as follows

$$T = T_0 + P_{bin}\, E + \sum_k \frac{K_{bin,k}(1 - e_k^2)}{1 + e_k\, cos\, \nu_k} sin\,(\nu_k - \bar{\omega}_k) \tag{6}$$

Here T_0 is the arbitrary fiducial mid-eclipse time, P_{bin} the binary period and E the cycle number. The five free parameters for planet k are the orbital period P_k (which is present in the equation through the true anomaly ν_k as it progresses through 2π over P_k), the eccentricity e_k, the longitude of periastron $\bar{\omega}_k$, the time T_k of periastron passage, and the amplitude of the eclipse time variation $K_k = (a_{bin,k} sin\, i_k)/c$ where $a_{bin,k}$ is the semi-major axis of the binary center of mass around the entire system's center of mass (Beuermann et al. 2010).

Using a Levenberg-Marquardt routine, the best fit for a one-planet model (Model 1) can be seen in Figure 17. The resulting orbit has a large eccentricity (> 0.65) and an orbital period of 22.6 years. However, the reduced χ^2 is 23.38, showing that the residuals on shorter timescales are highly significant. Under a two-planet model, two solutions present themselves: Model 2a with a χ^2 of 0.78 and a orbital period ratio of 2:1, and Model 2b with a χ^2 of 0.80 and a orbital period ratio of 5:2. Model 2a plotted against the data and its residuals can be seen in Figure 18. Clearly the residuals match on both long and short time scales, giving validity to the two-planet fits.

Table 4. Parameters of the one and two planet models

Model	P_c (yrs)	P_d (yrs)	e_c	e_d	a_c (AU)	a_d (AU)	M_c ($M_{\rm jup}$)	M_d ($M_{\rm jup}$)	χ^2_ν
1	22.60		> 0.65		6.91		8.36		23.38
2a	15.50	7.75	$\equiv 0$	0.20	5.38	3.39	6.91	2.28	0.78
	$\pm$ 0.45	$\pm$ 0.15		$\pm$ 0.02	$\pm$ 0.20	$\pm$ 0.10	$\pm$ 0.54	$\pm$ 0.38	
2b	16.73	6.69	$\equiv 0$	0.23	5.66	3.07	5.92	1.60	0.80
	$\pm$ 0.26	$\pm$ 0.40		$\pm$ 0.04	$\pm$ 0.06	$\pm$ 0.13	$\pm$ 0.40	$\pm$ 0.27	

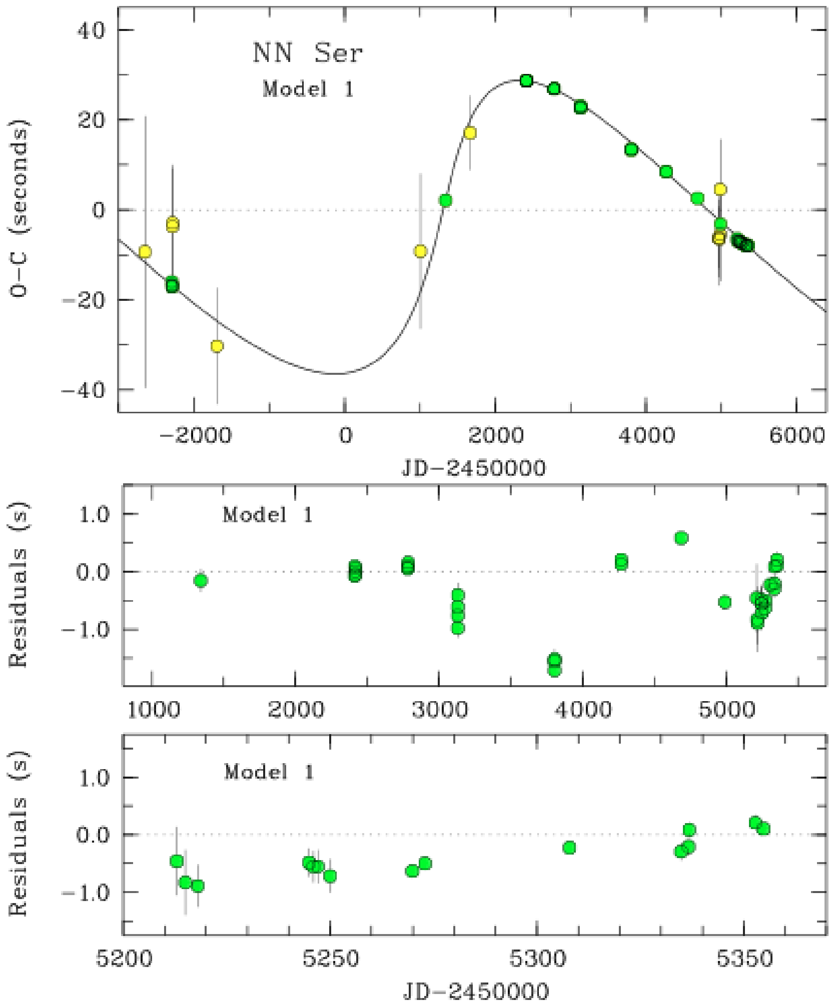


Fig. 17.—: *Top:* O-C of mid-eclipse times relative to the best fit linear ephemeris for the one-planet Model 1. *Center and Bottom*: Residuals of Model 1 for two selected time intervals. That is, the model is converted to a straight line and the data points are plotted around it. It is easier to see the deviations of the observed mid-eclipse times from Model 1 using this method.

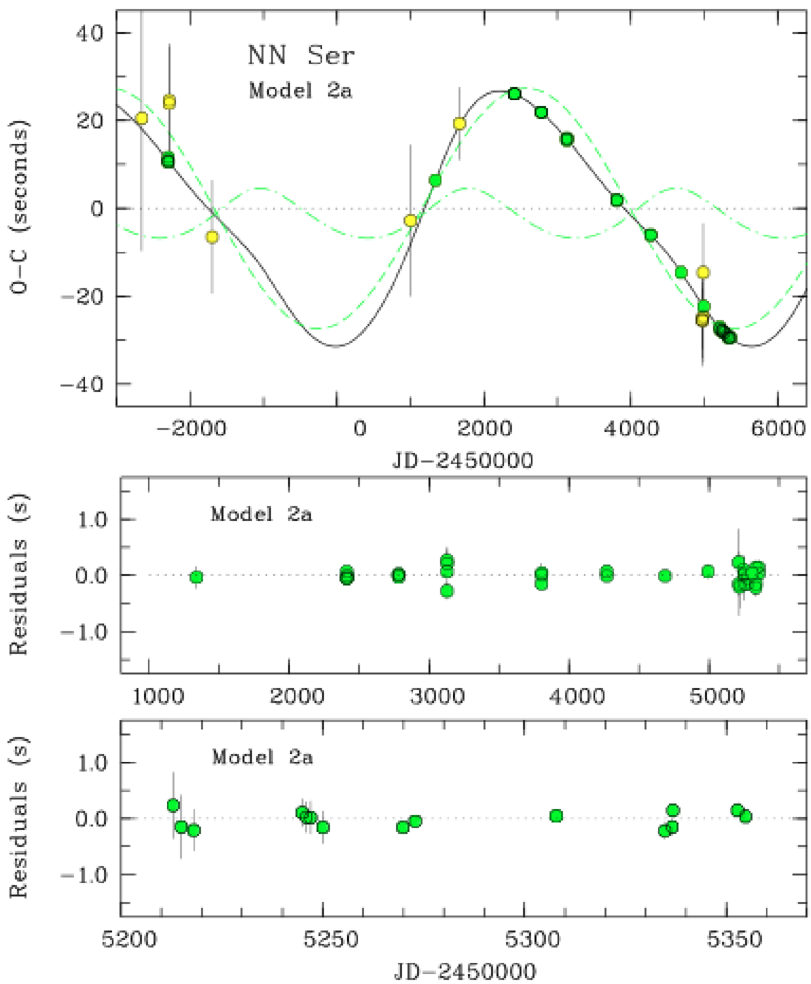


Fig. 18.—: *Top:* O-C of mid-eclipse times relative to the best fit linear ephemeris for the two-planet Model 2a. *Center and Bottom*: Residuals of Model 2a for two selected time intervals.

3.6. Discussion

The fact that the residuals of the two planet fit vanish almost entirely, both on long term (multiple years) and short term (first half of 2010) time scales, gives a large credence to the two-planet fit and places tight constraints on other possible methods. While the ages and lives of NN Serpentis' stars are well known, given the violent common envelope phase in their history, the lives of NN Ser's planets are considerably more mysterious.

Historically, the CE phase has been extraordinarily difficult to model. As mass is transfered onto a star within an interacting binary system, the impact of this matter with the stellar surface can generate energy. Because gravity is much greater at the surface of a white dwarf than a main-sequence star, the luminosity generated by this process can actually resist the infall of additional matter. Thus, some of the mass is not transfered at all to the companion but will go into orbit around *both* stars. The gas present in this common envelope will tend to resist the motion of the two stars, thus creating orbital drag and causing the orbital period to decay. Eventually, the gravitational energy created by this decaying orbit matches the gravitational energy binding the common envelope. At this point, any additional energy created by infalling matter will blow away the common envelope, leaving behind systems such as NN Serpentis.

Two possible formation scenarios exist for the formation of planets around NN Ser. The planets could be first generation, having existed before the system's CE phase and miraculously surviving their host star's fiery death. The effect of the frictional drag created by the CE on orbiting planets, however, is very complex and currently unknown. Simple Newtonian mechanics would imply that the system's mass loss would cause pre-existing planets to substantially move outward and potentially even be lost. Given that the CE is sufficiently dense and expands slowly, however, orbital drag from tidal forces will also cause the planets to move inward and potentially counter this outward movement. Ultimately, since the degree of orbital drag of a CE on pre-existing planets is unknown, the initial conditions of these planets has a wide array of possibilities. Endeavors to model this process have great promises for future research.

The second possible scenario is that the planets are second generation, created from the matter cast off after the CE phase. Since 3/4 of the system's mass is lost during a CE, there is certainly sufficient mass present to create planets (even more so than classic proto-planetary disks). Yet, it is unclear how the planetary nebula from a CE evolves over time and how a rotating, circumbinary proto-planetary disk could be created from this aftermath. If the expelled gas is supersonic, how would shock waves affect the formation of planets? If the gas is subsonic, how much matter "returns" to the system to create a proto-planetary disk? Furthermore, the gas in this planetary nebula is far more enriched than typical proto-planetary disks and the effect of this high metalicity on planet formation is open for discussion. Perhaps the answer is a combination of both scenarios: a 1st-generation asteroid size object transforming itself into a 2nd generation Jupiter-size planet. Whether these questions can ever be answered is unknown, but unique planetary systems such as NN Serpentis certainly expand the field of exoplanet research into new and exciting areas.

4. Conclusion: A Reflection on the White Dwarf FRI Stream and Advice to Incoming Students

The Freshman Research Initiative at the University of Texas at Austin began in 2005 as an opportunity for entering freshmen to gain first-hand experience in real research labs. While initial "streams" focused mostly on biology and chemistry, Don Winget and Mike Montgomery began the White Dwarf Astronomy FRI stream in 2009. As of 2012, The WD stream has admitted 6-8 students per year with interest in astronomy research. The stream has a tiered organizational structure, flowing from the PI (Don Winget) and the research educator (Mike Montgomery) to a graduate student TA and undergraduate mentors. The first semester of each new group (beginning in the spring) is divided into two separate components. For the first half of the semester, students complete planned labs designed to teach them facets of WD astronomy ranging from basic knowledge of UNIX to light curve analysis. During the second half of the semester, each student is assigned an *individual* research project which he/she works on. Each of these projects is on the frontier of research with unknown solutions and the potential for future exploration. While students during the first semester often must be guided by their mentors/TAs, the students are encouraged to work much more independently during the second semester. Throughout the entire year, there are weekly lectures delivered by the research educator (Mike Montgomery) beginning with the basics of "what is a white dwarf?" and leading toward more complex concepts.

I was among the first students to enter the WD FRI stream in 2009, and have been a peer mentor for the next three years. As the first among the graduating white dwarf FRI students, I have a unique perspective on its impact on student success. It is my goal, therefore, for this work to serve as a guide for younger FRI students, explaining how one can get the most out of this wonderful opportunity presented to them. For myself, the FRI made a profound impact on my development as a scientist and I hope it will yield the same results for every future entering freshman.

The foremost lesson I can impart on younger students is the importance of getting your hands dirty with research. Astronomy is an enormous field, and to fully understand even something as specific as white dwarf stars is a near impossible feat in four short and busy undergraduate years. Research is the key to unlocking any understanding of astronomy as an undergraduate. The practice of thinking critically about your work is far more valuable than reading about someone else's. Reading textbooks and journals is necessary to gain an understanding of the field, yet asking the question "*what could possibly make my data look like this*" is considerably more insightful than thinking "*their data looks like this because the author says so*". When reading a journal, I find it more important to take away *how* the research was carried out than the actual results. Research also has an important psychological aspect. As a freshman entering research, I felt drastically inferior to those above me. *How can I possibly ever understand as much as they do?* Yet, I remember the ecstatic pride I felt when obtaining my first results. I had discovered something about the universe that no one else knew. From that moment on, I knew that I could succeed in astronomy.

The key to doing research as an undergraduate is persistence and dedication. Rarely are interesting problems ever thrown at you and rarely can interesting results be achieved without hard work. Your professor and advisors are wonderful resources, particularly in the first stages of your learning, yet you must take the initiative in your own research. Always ask yourself "*what is the next level I can take this project*". To be selected to work on NN Serpentis with the University of Göttingen, I had to show eagerness and ambition towards the project. I was initially trained to use the MONET telescope as a student resource for school teachers using the telescope for outreach. The decision to develop the MONET for time-series white dwarf photometry was purely on my own accord and I became the first astronomer at UT to use the telescope for research. You are in charge of your own research, and it is solely up to you to make your research stand above others.

At the same time, you must learn to effectively use all the resources at your disposal. Perhaps the most important of these resources is your own peers. Establishing good relations with your fellow students is not only essential for your research, but your growth and happiness as well. Whenever I have a question regarding my research, be it a computer code that isn't working properly or a problem reducing a night's run, I always first turn to the student's working in my lab. Having a conversation about your research is one of the best ways to understand it, and there are no better listeners than your fellow struggling peers. Over the four years I have worked in the white dwarf lab, I have grown to deeply cherish the friends I made my first year. They both keep me sane and deepen my passion for astronomy.

I am confident that I owe most of my success in astronomy to the white dwarf FRI stream. Without the motivation FRI placed on me, I doubt that I would have built the courage to begin research until well into my undergraduate career. Beginning research as a freshman impacted my entire undergraduate development, from classes to general excitement about the field. The FRI astronomy stream has trained me to be an astronomer, a researcher, a peer, a collaborator, and foremost a thinker. I have had the wonderful opportunity to watch the program transform the future of three entering classes of freshmen just as it transformed mine. While I leave to continue my career elsewhere, I am gratified and humbled to leave the future of my work in fully capable hands.

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