Searching for Unresolved Binary Brown Dwarfs in the Hubble Archives

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A senior thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Bachelor of Science

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August 2015

ABSTRACT

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The inability to resolve close stars due to the Rayleigh criterion complicates the search for closely orbiting binary brown dwarf systems. We have developed a Fortran computer program that uses point spread function fitting on Hubble archive data to find binary systems at separations that are visually unresolvable. To test the performance of this program under the full range of parameters (brightness, separation, position angle, background noise), we have created and analyzed six hundred thousand simulated binary data sets. The results from this test suggest that our program should be able to successfully identify binary systems at separations of less than a pixel. In particular, we can place limits of around 90 percent certainty that the brown dwarf star BD0559 is actually a binary system with a separation of 0.035 arcsec.

Keywords: Brown Dwarfs, Point Spread Function, Binaries

ACKNOWLEDGMENTS

I would like to thank the Brigham Young University Physics Department for supporting and funding this research.

I would also like to thank my research advisor, Dr. Denise Stephens, for providing the opportunity to work on this project. She has been a great teacher and guide. Her husband, Dr. Tom Stephens, was also a great help for overcoming the programming challenges involved.

I am also grateful to Elora Salway and Christina Cole who performed a lot of the data analysis of the Hubble archival data.

I would also like to thank my wife, Kimberly Gardner, who has been a constant source of encouragement.

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Chapter 1

Introduction

The purpose of this work is to determine the extent to which we can use a point spread function fitting technique to find binary brown dwarf systems in the Hubble archives. First, we present a background of brown dwarfs, the importance of binary systems, and how point spread fitting works.

1.1 Brown Dwarfs

Brown dwarfs are considered failed stars. Like a star, they form via gravitational collapse, but they don't reach high enough temperatures to ignite hydrogen fusion in their cores. This results in brown dwarfs slowly cooling and becoming fainter over time. Their atmospheres evolve from resembling a low-mass star (T 300K) to looking like a hot gas giant planet (T 1000K).

In contrast, the fusion inside of stars provides a stable source of energy and keeps their luminosity constant during their main sequence lifetime. The minimum mass required to reach the temperate required to fuse hydrogen to helium is approximately 0.08 solar masses (Kumar 1963). Thus if you could directly measure the mass of a low-mass object, you could theoretically determine if it was a star or a brown dwarf.

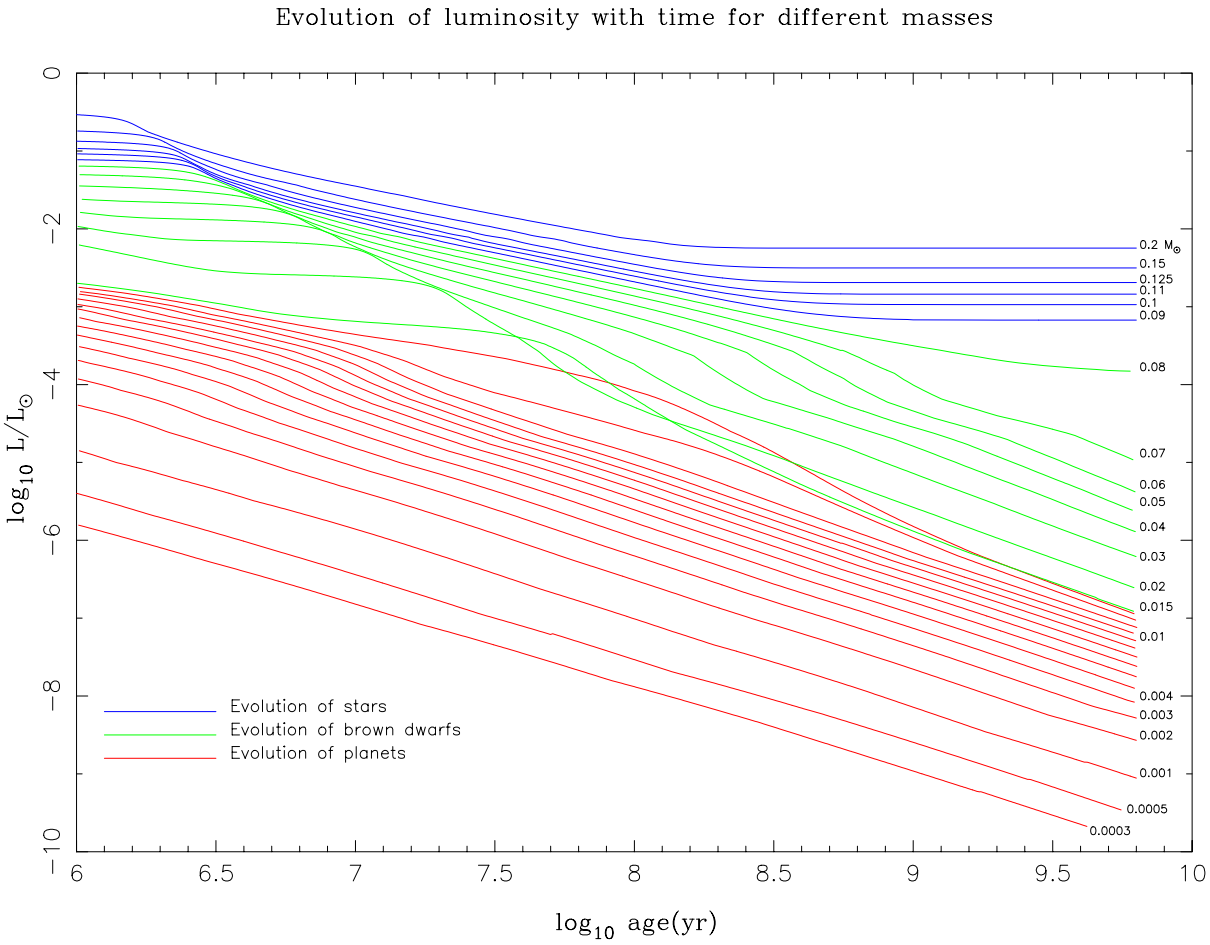


Figure 1.1 Luminosity versus age of stars (0.09 $M_{\odot}$ and greater), brown dwarfs (0.015-0.08 $M_{\odot}$), and planets (less than 0.015 $M_{\odot}$) (Reproduced from Burrows 1999).

The initial luminosity of a star or brown dwarf depends on the amount of mass that collapsed to form the object. Figure 1.1 shows how luminosity changes with time for stars, brown dwarfs, and planets. It can be seen that the luminosity of stars stabilizes once hydrogen fusion begins, and thus there exists a clear relationship between luminosity and mass. Brown dwarfs, however, continue to grow fainter their whole lives and no clear relationship exists between luminosity and mass. This means that when we observe a bright brown dwarf we have no way of knowing if it is an older

more massive brown dwarf, or a younger less massive brown dwarf, as both could have the same luminosity.

1.2 Binary Systems

There is no method to directly determine mass solely through the observation of a lone object. Binary systems, in which two stars orbit each other, are crucial to determining a star's mass. When we observe a binary system, we measure the relative separation and position angle of the two objects. Multiple observations are made over several years to monitor how these two parameters change with time, until an orbital period P can be determined. If the distance to the system is known and an inclination for the orbit can be found or estimated, we can then find the average physical separation of the two objects a, or semi-major axis of the orbit. Using Newton's version of Kepler's third law,

$$P^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)} \tag{1.1}$$

and the equation of center of mass,

$$x_{cm} = \frac{m_1 x_1 + m_2 x_2}{m_1 + m_2} \tag{1.2}$$

we can then calculate how massive each star is. It is through the observations of binary systems that the relationship between mass and luminosity for stars was first discovered (Kuiper 1938).

Many brown dwarfs are in binary systems with main sequence stars, however these systems typically have separations of 100s of AU. This makes their orbital period too big for practical observation; we would have to observe them over the course of 100s of years to determine an orbit. Binary systems where the two objects are closely orbiting brown dwarfs are fairly abundant (Burgasser et al. 2003). It appears these systems are created when a low mass star breaks into two objects during formation.

Understanding closely orbiting brown dwarf systems is crucial to placing constraints on our star formation theories. The problem is that these objects orbit so closely they are hard to resolve as two separate objects and measure the orbital parameters. Only four binary brown dwarf systems exist whose masses have been determined from measurements of their orbital parameters. When these objects are compared to theoretical models (such as that in Figure 1.1), their masses are larger than what is predicted based on their age and luminosity. This indicates that there is a problem with our models of brown dwarf evolution.

In order to correct our theoretical models, we need more than just four data points to compare to. This means we need to calculate the orbits and determine the mass of several more binary brown dwarf systems to find the trends in agreement as a function of mass, temperature, age, etc. Using only the binary systems that have been visually resolved has not yielded a sufficient amount of data. In this paper we discuss the ability of using point spread function fitting of binary brown dwarf systems observed by HST to find new binaries. These binaries will provide more data against which we can compare our models.

1.3 Point Spread Function Fitting

The point spread function (PSF) describes the way that the light of a star spreads out on the CCD camera of a telescope. The PSF is dominated by diffraction through the circular aperture of the telescope. This causes the rings seen in Figure 1.2. Almost all modern research telescopes use a primary mirror to focus the light and a secondary mirror to reflect the light onto the CCD. The secondary mirror is held up by crossbars which also cause diffraction of the light and create the diagonal beams seen in Figure 1.2. These diffraction features need to be taken into account when modeling the PSF of a telescope.

Modeling the PSF of an Earth-based telescope is very difficult due to atmospheric refraction

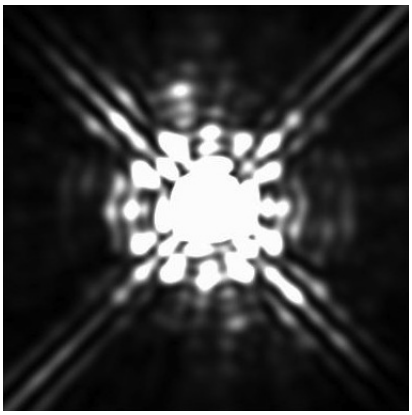


Figure 1.2 PSF generated by the Tiny Tim program for filter F110W on the NICMOS2 camera

that constantly changes throughout the night. Space based telescopes, however, are not affected by atmospheric distortion and their PSFs can be modeled reliably. Tiny Tim (Krist et al. 2011) is a program that was written exclusively to generate model PSFs for Hubble Space Telescope (HST) data. It takes into account the camera, filter, position on the chip, and the spectrum of the star being observed to generate an accurate PSF.

Identification of binary systems is dependent on our ability to visually resolve the two stars. The limit beyond which we can no longer resolve two stars is known as the Rayleigh criterion. Figure 1.3 shows an illustration of what happens when the stars come closer than this limit. The figure gives both a one dimensional and two dimensional representation of the PSF.

PSF fitting has been shown to be effective in identifying candidate binary systems that are unresolvable and appear to be a single object (Stephens & Noll 2006). The method involves using a model PSF and changing the position and flux of the PSF until the best possible match to the data is obtained. This single PSF fit represents what we would see if the star we are observing truly is only one star. We then use two PSFs and change the positions and relative fluxes (brightnesses) until we get the best match. This represents the case that the star is actually a close binary system. Comparison of the chi squared (defined in Section 2.2) of the two fits allows us to determine the

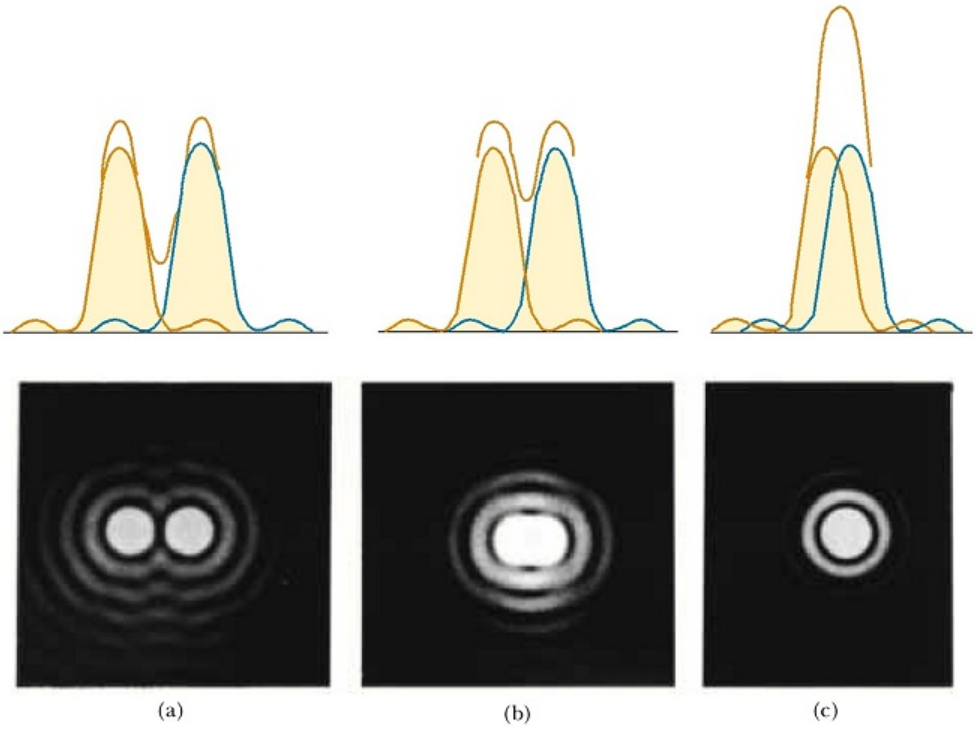


Figure 1.3 (a) two stars that are well resolved, (b) two stars that are at the limit of resolution (Rayleigh criterion) (c) two stars that are unresolvable (Reproduced from http://www.kshitijiitjee.com/Study/Physics/Part7/Chapter38/30.jpg)

probability of the star being a binary or not.

1.4 BD0559

PSF fitting has great potential, but we need to be able to show that it works in brown dwarf binary systems. To do this, we have chosen a brown dwarf that many believe to be an unresolved binary system.

The brown dwarf star 2MASS J05591914-1404488 (hereafter referred to as BD0559) was first discovered by Burgasser et al. (2000). It is classified as a T4.5 spectral type brown dwarf. However, it is significantly brighter than a typical T4.5 brown dwarf star (Vrba et al. 2004). This has led to the

suspicion that BD0559 is actually a close orbiting binary system, but no telescope on the ground or in space has been able to successfully resolve this object. This paper attempts to provide solid evidence that BD0559 is a binary system.

Elora Salway has done the data reduction from the HST archives for the NICMOS cameras (Salway 2015). Christina Cole reduced the data for the ACS, WFC2, and WFC3 cameras. In this paper, we will summarize their conclusions and discuss their implications in the broader scope of PSF fitting in general.

1.5 Overview

The study of brown dwarfs has shown us that we don't yet fully understand the initial temperature and luminosity that a brown dwarf may have when it forms. Neither do we understand how it will cool and evolve over time. We need to find more binary systems so that we can determine their masses and refine our theories. Our purpose in this paper is to determine the limits of a PSF fitting technique in identifying binary brown dwarf systems.

The remainder of this paper is organized as follows. Chapter 2 details the method used to detect binaries. Then we will discuss how to test this method to determine its limitations. Chapter 3 will present the results of this analysis and the implications of our findings. For those interested in continuing this work, a user's guide is contained in Appendix A.

Chapter 2

Method

2.1 Cameras and Filters

We reduced data on BD0559 and ran models for four different HST cameras, the Wide Field Planetary Camera 2 (WFPC2), the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), the Advanced Camera for Surveys (ACS), and the Wide Field Camera 3 (WFC3). In this thesis I will focus on the results from the NICMOS 1 and NICMOS 2 as the program and technique utilized is identical from one camera to the next.

We have data of BD0559 from four filters in NICMOS 2 and six filters in NICMOS 1. The cameras and filters were chosen to cover wavelengths in the infrared regime from 0.90 μm to 2.2 μm. For comparison, the spectrum of BD0559 peaks at a wavelength of 2.9 μm. The filters and their properties are presented in Table 2.1. The filter names are designated by three numbers corresponding to the central wavelength of the filter and a letter signifying if the filter width is wide (W), narrow (N), or medium (M).

Camera (NICMOS)	Filter	Central Wavelength (μm)	Full Width Half Max (μm)
1	F090M	0.90332	0.1731
1	F108N	1.0816	0.0099
1	F110M	1.1016	0.1982
1	F113N	1.1298	0.0113
1	F145M	1.4546	0.1963
1	F165M	1.6478	0.1985
2	F110W	1.1246	0.5261
2	F180M	1.7970	0.0686
2	F207M	2.0826	0.1524
2	F222M	2.2177	0.1455

Table 2.1 Filters and Cameras on the Hubble Space Telescope

2.2 Point Spread Fitting Program

In our search for binary brown dwarfs, we use a modified version of a computer program written by Stephens & Noll (2006) to search for binary trans-Neptunian objects. This program requires a model PSF with which to generate solutions. We use the Tiny Tim program to produce a PSF for each camera and filter. Tiny Tim will be discussed in more detail in section 2.2.2.

The binary detection program works by minimizing the residual (χ^2) of the data. The formula for the χ^2,

$$\chi^2 = \sum_{pixels} (Flux_{data} - Flux_{fit})^2 * \sqrt{Flux_{data}} \tag{2.1}$$

is modified from Press (1992). The program calculates the residual by taking the flux from the actual data and subtracting the flux from the calculated fit. The formula for χ^2 presented in Press

(1992) requires each data point to be weighted by the standard deviation. In our algorithm, the square root of the flux is used as the weight in order to prevent the couple of pixels with most of the flux from dominating the fit. Using the square root gives the happy result that the brightest pixels don't dominate as heavily while the pixels with little to no flux have little impact.

Our detection program begins by dividing each pixel into a 10x10 grid. Each grid point is separated by 0.1 pixel. The user specifies a list of pixels to use when searching for the position of the primary star, and a list of pixels to use for the secondary. The program takes a Tiny Tim PSF and puts it centered on the bottom left corner of the first primary pixel. This represents the primary star. The program then adds a second PSF at the bottom left of the first secondary pixel to represent the secondary star. The program adjusts the brightness of each in order to find the best match to the actual data, determined by minimizing χ^2. It then moves the secondary to the next grid point and repeats the process, testing all positions in this pixel and recording the best fit.

Once all the positions for the secondary star have been tested, the program moves the primary star to the next grid location and starts the process over again. This is repeated until every combination of primary and secondary location has been tested. The combination with the smallest residual value is output to the user as the most likely location for the primary and secondary object in those two pixels. It also reports the relative flux that each model PSF must be multiplied by in order to match the profile of the observed brown dwarf. This process is repeated for every primary and secondary pixel specified by the user.

2.2.1 Changes to Program

The program written by Stephens & Noll (2006) was written several years ago and was not well documented. Modifying this program to work for our purposes was my major contribution to this project. Following are the major changes from the original program.

The program was written to only work for one filter on one camera of the HST. Changing

from NICMOS 1 data to NICMOS 2 data presents the challenge that the PSF is a different size, changing from a 17x17 pixel image to a 67x67. Instead of assuming the size of the PSF to be 17x17, the program needed to accept the dimension as an input parameter and use that value in the calculations.

Another challenge is that the relationship between flux and magnitude is

$$2.5 * \log_{10}(Flux) = c * Magnitude \tag{2.2}$$

where c is a filter dependent constant. Because we analyzed several filters, the program needs to be able to accept the constant as an input parameter.

Another major roadblock was the speed of the program. The original program took about 20 minutes to complete one set of data. Since we wanted to analyze several filters, this made it difficult to generate enough data to be statistically significant. To fix this, I changed the program to store the important data in an internal array instead of reading it from file. This sped up the program to be able to complete one data set in an average of seven seconds.

2.2.2 Tiny Tim

Tiny Tim is a program written in 1992 to generate model PSFs for HST data (Krist et al. 2011). It has become the standard method of modeling the PSF of the Hubble Space Telescope. To accurately model the PSF, Tiny Tim needs several inputs. In the following paragraphs, we will discuss each of the needed inputs so we can see how they may affect our results.

First we specify the camera that was used. This is important because each camera has a different plate scale (how much of the sky is imaged per centimeter on the CCD) and this will affect how well the PSF is sampled. A smaller plate scale corresponds to a higher resolution in the PSF.

We must also specify which pixel on the CCD the star is centered on. The PSF will change slightly depending on where the center position is due to geometric distortion of the light. We can't

	Primary Magnitude	Delta Magnitude	Separation (pixels)	Background Noise
Starting Value	14.0	0.0	0.1	Representative of each filter
Step Size	0.5	0.5	0.1	Representative of each filter
Ending Value	18.0	4.0	1.0	Representative of each filter

Table 2.2 Starting values, step size, and ending values of each parameter

feasibly test every possible center position. Instead, we limit ourselves to a representative position for BD0559 in the data we have obtained, which tends to be the upper right of the CCD.

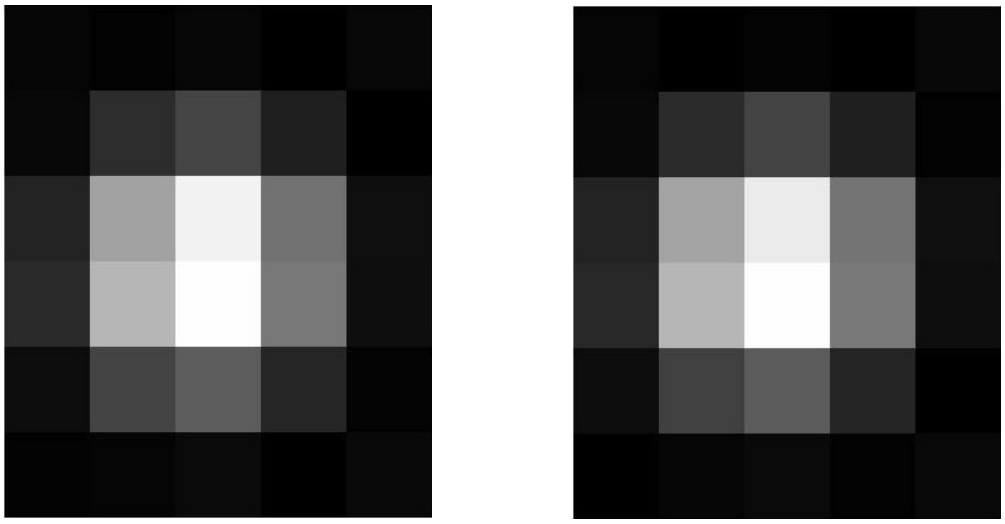
Lastly, we specify both the filter and the spectrum of the star we are analyzing. The spectrum of the star tells Tiny Tim how much light the star outputs for each wavelength and the filter specifies how much light the telescope lets through at each wavelength. Tiny Tim then calculates how each wavelength will diffract and adds together the effect of each wavelength to create the final PSF. The wavelength dependence is important as each wavelength will have a different level of resolution determined by

$$\theta_{resolved} = 1.22\ \lambda / D \tag{2.3}$$

where $\theta_{resolved}$ is the minimum angle of resolution, λ is the wavelength of light, and D is the diameter of the telescope. We used a typical spectrum for a T-5 brown dwarf.

2.3 Generating Simulated Binaries

To accurately test the detection limits of our program we need to generate simulated data that accurately represents the actual Hubble data. To do this, we use a technique that involves combining two PSFs produced by Tiny Tim and adding noise to simulate the real data. Fig 2.1 shows a side



(a) Hubble Datal **(b)** PSF Model

Figure 2.1 Comparison of (a) actual Hubble data and (b) data simulated using model PSFs

by side comparison of actual data and an image produced by this technique.

To test for a wide range of parameters, we created 2100 sets of data for each trial. Each set of data has a specified primary brightness, secondary brightness, separation, and noise level. These values are varied within the bounds specified in Table 2.2.

The program that creates the simulated binary data begins by randomly selecting a center position for the primary star. It shifts the PSF created by Tiny Tim to this position and scales its brightness to be the specified magnitude. The program then randomly picks a position angle to place the secondary star and shifts another PSF to the specified separation at that angle, again scaling its brightness to the appropriate level. Lastly, it adds the background noise typical for the HST, using a random number generator to add noise to each pixel, within the bounds of a Gaussian distribution. We change the input parameters until we have all 2100 sets of data for that trial.

In order to generate enough data to be statistically significant, we run 30 trials for each filter. Each trial uses a different seed for the random number generator so that the positions and angles are different each time. This way we have 30 data points for every combination of primary magnitude,

secondary magnitude, separation, and background noise level. Thus, for each filter we have 61 000 data sets that we run through our detection program. With 10 filters, that gives a total of 610 000 data sets for the NICMOS cameras.

2.4 Analyzing the Binary Fits

After generating the simulated data, we run each data set through the detection program we use to find the real binary systems. As the program analyzes each data set, it records the parameters of the fit with the lowest χ^2. This includes the position of the primary star, the position of the secondary star, and the brightness of each. From these values we calculate the separation, position angle, and relative fluxes of the stars.

We compare the results obtained from the program to the actual values that were used to create the data set. For each data set we compare the calculated and actual separations, position angles, relative fluxes, and position on the chip. For each of these value we generate either a yes or no, depending on whether the fitting routine found the correct answer within the error ranges described in the next paragraph.

We chose our ranges so that the calculated values would be counted as correct in the following situations, which are the minimum certainty we need to calculate a fit for the orbits of the two stars. The separation must be correct to within 0.2 pixels. The position angle must be correct to within 10 degrees. The difference between the ratio of the fluxes must be less than 3. And the position on the chip must be within 0.1 pixels. Each parameter was analyzed separately; so we have four entries for each data set, either a yes or a no for each parameter.

To visualize the results we count the number of times the program returned a yes for each combination of input parameters then divide by the number of trials. This gives the percentage of trials that were successfully identified for a given primary magnitude, secondary magnitude,

separation, and background noise. To visualize the results, we create heat maps that are presented in Section 3.1.

Chapter 3

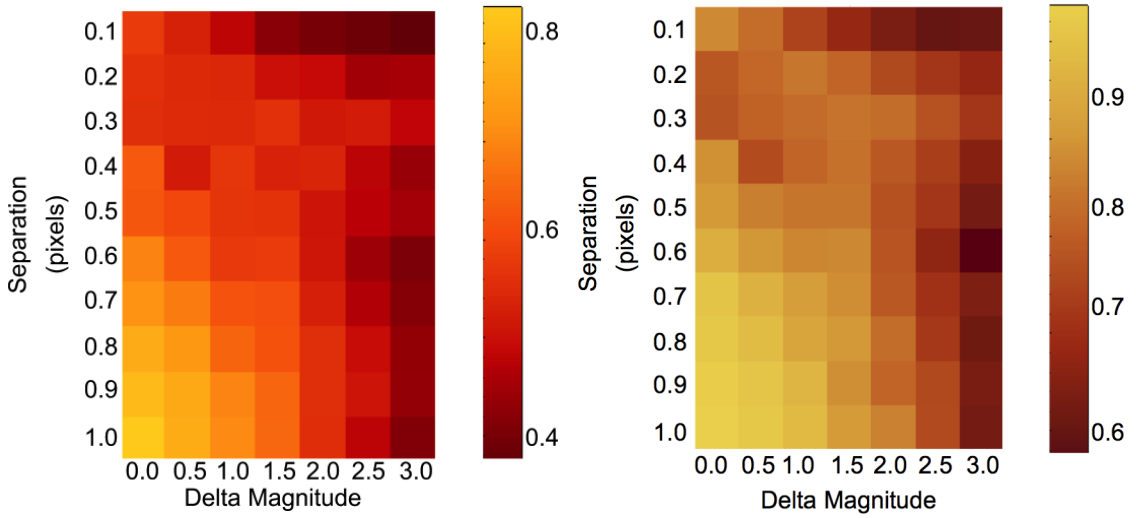
Results and Conclusions

3.1 Detection Limits

In order to visualize the results, we produced heat maps of the data. The heat maps plot the percentage of trials that yielded a yes within the limits described in Section 2.4. We analyzed 10 filters and created four heat maps per filter. Because each filter tends to follow the same trend, we only present a representative subset of the heat maps. The other filters have similar patterns, only the actual values differ.

3.1.1 Separation

In Figure 3.1, we present two heat maps that are representative of the trend for identifying the correct separation between the stars. These plots show a high probability of finding the correct separation in the bottom left of the graph. This corresponds to two equally bright stars that are a pixel apart on the CCD. As the separation decreases (moving up on the graph) and the secondary star gets fainter with respect to the primary (moving to the right on the graph) the probability of detection decreases.



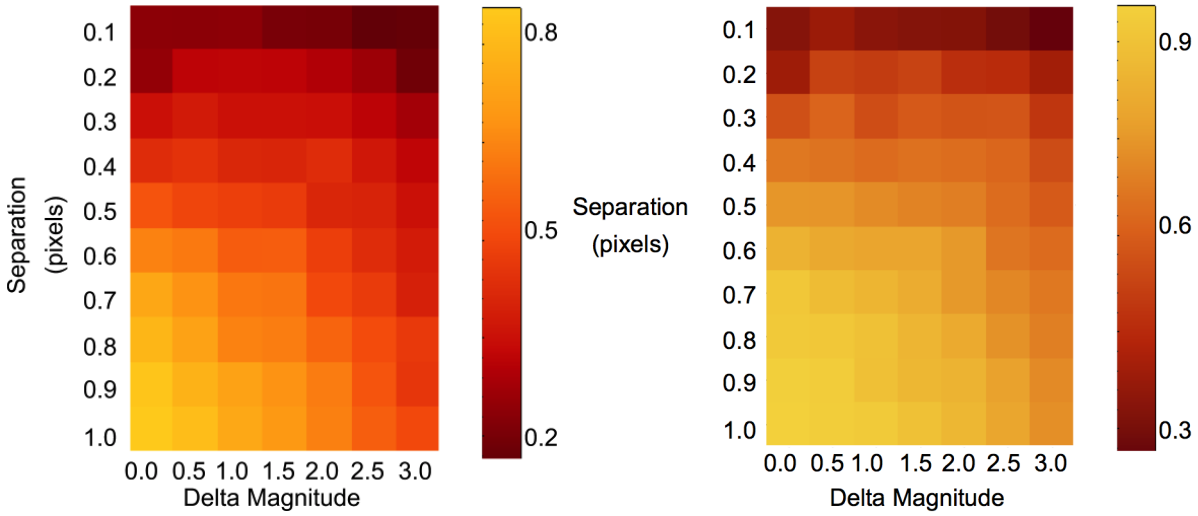
(a) f180m **(b)** f090m

Figure 3.1 Heat map showing the fraction of runs that yielded the correct separation for (a) filter 180m on NICMOS 2 and (b) filter f090m on NICMOS 1. The horizontal axis is the difference in magnitude between the secondary and primary and the vertical axis is the separation between the stars in pixels. Note that the color scales are different in each map.

3.1.2 Position Angle

In Figure 3.2, we present two heat maps that are representative of the trend for identifying the correct position angle between the stars. These graphs show a very similar pattern to those of the separation. We are most likely to find the correct position angle when the stars are the same brightness and far apart.

In order to determine the orbit of the two stars we need to be able to measure the separation and angle. These results indicate that we should be able to reliably measure both these parameters down to a separation of 0.5 pixels for equally bright stars. For comparison, the minimum separation necessary to visually resolve two stars is at least 1.5 pixels (using the NICMOS 1 camera). This is a promising result that shows the ability of PSF fitting to reveal binary stars beyond visual resolution limits.



(a) f180m **(b)** f090m

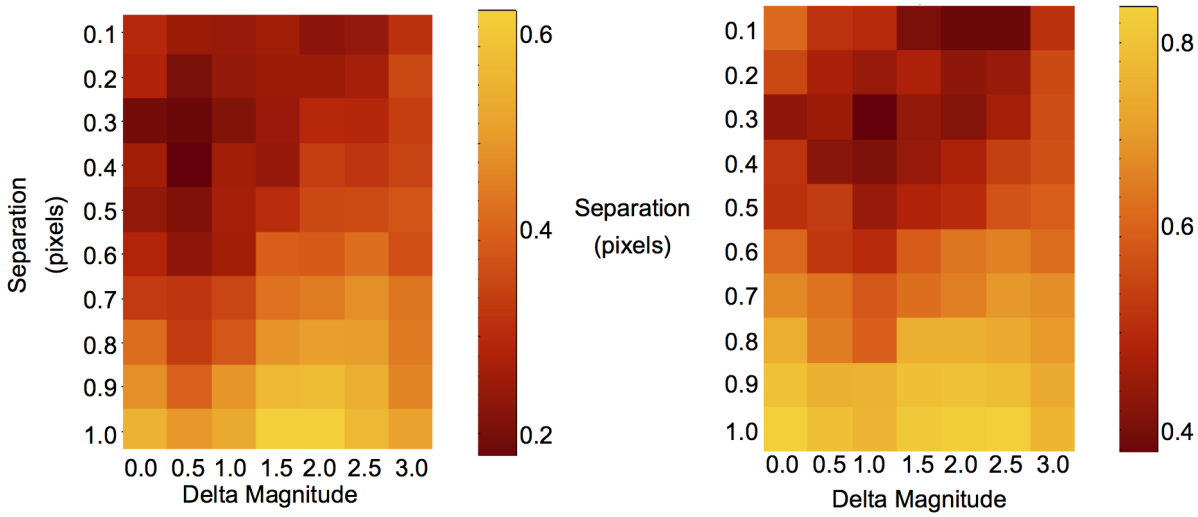
Figure 3.2 Heat map showing the fraction of runs that yielded the position angle for (a) filter 180m on NICMOS 2 and (b) filter f090m on NICMOS 1. Note that the color scales are different in each map.

3.1.3 Relative Flux

Figure 3.3 shows two heat maps that are representative of the trend for identifying the correct relative flux between the stars. These graphs do not show the same pattern we have seen from the other two sets of graphs already presented. The highest probability is centered towards the bottom right of the graph. This corresponds to a higher likelihood of getting the relative fluxes correct when the two stars are separated by a pixel and the secondary star is dimmer than the primary.

Measuring the brightness of each star in each filter is the only way to determine temperature. Typically, the temperature of a star is measured using spectroscopy to find the peak wavelength in the spectrum. With these two stars so close together it is impossible to distinguish the spectra of the two stars from one another. By measuring the flux in multiple filters we can find which brown dwarf spectral type fits the data and use the correlation between spectral type and temperature.

This means there is the highest probability of determining the correct spectral type when the secondary star is 2 magnitudes fainter than the primary star. But we have the highest probability



(a) f180m **(b)** f090m

Figure 3.3 Heat map showing the fraction of runs that yielded the correct relative fluxes for (a) filter 180m on NICMOS 2 and (b) filter f090m on NICMOS 1. Note that the color scales are different in each map.

of measuring the correct orbit when the two stars are equally bright. It seems that PSF fitting can reliably determine either the orbit or the spectral type, but not both.

3.2 Implications

A comparison of the graphs presented shows that for a given separation and delta magnitude we have a higher probability of finding the correct binary solution in NICMOS 1 than in NICMOS 2. This is most likely due to the smaller plate scale of NICMOS 1. The plate scale of NICMOS 1 is 0.043 arcsec/pixel while that of NICMOS 2 is 0.075 arcsec/pixel. The PSF of the star is better sampled in the NICMOS 1 camera and thus leads to a better solution.

We can also see that the probability of successful detection varies with the central wavelength of the filter. For filters centered around the wavelength where the airy disk of a brown dwarf is larger, it is less likely to find the correct binary fit. This is because the PSFs are more spread out

Camera	Filter	Separation (pixels)	Primary Magnitude	Secondary Magnitude	Probability Separation	Probability Pos Angle	Probability Relative Flux
1	F090M	0.83	17.0	17.9	0.91	0.91	0.59
1	F108N	0.85	14.6	15.5	0.90	0.93	0.58
1	F110M	0.73	15.0	16.2	0.79	0.91	0.50
1	F113N	0.96	15.2	16.4	0.90	0.96	0.60
1	F145M	0.92	15.1	16.3	0.56	0.90	0.19
1	F165M	0.72	14.1	14.8	0.49	0.69	0.10
2	F110W	0.38	14.8	16.3	0.98	0.94	0.85
2	F180M	0.36	14.8	16.3	0.82	0.68	0.35
2	F207M	0.42	13.6	14.8	0.86	0.74	0.37
2	F222M	0.59	14.4	15.3	0.68	0.72	0.20

Table 3.1 The values found for BD0559 in each filter for the NICMOS cameras and the probability of those values according to the limits analysis

and overlap. It's harder to pick out the two separate stars when the PSFs overlap so much.

There are some noise patterns in the heat maps that we don't fully understand. These are most apparent in Fig 3.3. We would expect a constant decrease in detection probability as the the separation between the stars decreases. Yet, around 0.3 pixels we see a sharp decrease than an increase in probability as separation decreases. This may be due to a selection bias in our program and is something we need to look into more.

3.3 Analysis of BD0559

We have discussed the results of this analysis in how it relates to PSF fitting techniques in general. Now we will discuss how these results apply specifically to our data of BD0559.

In Table 3.1 we present the average values of separation and magnitudes that were found for each filter by Salway (2015). In this table we also include the probability that we found the correct values according our simulated data analysis.

This table suggests that the values we found for separation and position angle are accurate to a high probability. For most filters, the probability is over 90 percent. We see that the results in filters F145M and F165M are the least accurate and may need to be given less weight in our analysis.

The probabilities of relative flux in Table 3.1 are significantly lower than that for separation and position angle. This means the values for magnitude found by Salway (2015) are not reliable. For this reason, we have been working on another method to determine the individual magnitudes of the stars. This method involves fitting brown dwarf spectral types to the combined spectral type for BD0559. The method and results are presented in detail in Wright (2015).

There are still some problems we have yet to address fully. The biggest is the variance in the position angle. The observed uncertainty in the separation and flux is well within the probabilities predicted in this paper. However, the position angle seems to vary much more than we would expect. We need to figure out why it varies and how to fix it so that we can measure the orbit of the star.

3.4 Conclusions

Point spread function fitting is a valuable technique that can be used to find binary solutions to apparently single objects. We have shown that this technique works with fairly high accuracy with separations as small as 0.5 pixels in some filters. If two stars are positioned closer that 0.5 pixels,

we are unlikely to be able to distinguish them as two separate stars.

The binary fit we have found for BD0559 has a high probability of being correct. We have shown that the separation and position angle values determined by Elora Salway are in the neighborhood where the theoretical analysis predicts ninety percent accuracy. The brightness, however, is under sixty percent certain.

3.5 Future Work

There is some disagreement in the position angles of Elora Salway's data. My analysis suggests that we should be able to determine the angle with the same accuracy as the separation. However, the data shows a consistent separation but a varying angle; varying as much as 20 degrees within data taken a couple of hours apart. We need to analyze the position angles and determine the cause of this variance.

We have only finished analyzing a small subset of the possible filters. We have data from the other three cameras on the HST and have finished running the simulated model analysis. The initial results look promising, but we are still working on how to figure out the magnitudes of the individual objects. The magnitudes need to be calculated before we can compare the results to the simulated models.

Once we have gathered enough data from all available cameras, we can use another best fit program to determine possible orbit solutions. We will use those solutions to predict when the two brown dwarfs will be have the largest separation. At the time of predicted maximum separation, we can observe BD0559 again and hope to be able to visually resolve the binary, or at least narrow down the possible orbit solutions. See Grundy et al. (2008) for more information about how this process works.

We have only looked at one potential binary system in the archival data. There are many more

brown dwarf stars that have the possibility of being binary. Now that we know which filters are the most reliable for finding binary systems, we can start our search for more binaries using those filters. This can open up the doors for many more discoveries of binary brown dwarf systems.

Appendix A

User's Guide

Having discussed the general algorithms the programs use and their scientific significance, it is now time to give some practical steps one could follow if they desired to continue on this project.

A.1 File Management

All the code and data is located on the BYU astronomy servers. The path file to follow is /data/BDbinaries/Doug/bd0559. Inside of this folder there is a folder for each camera that I have analyzed. These camera folders each have a folder for each filter analyzed on that camera, as well as a folder called necessaryPrograms.

The filter folders contain all of the actual data. There is a folder called psfModels, which stores the models created by Tiny Tim that are used for the fitting process. There is a folder called hmodels, which stores the single star models which are combined to create the simulated binary data. Then there are a series of folders called himagesXX, which contain a set of simulated data and the fits that were found for them. The final results for each himages folder is copied into the results folder.

After having spent time understanding how the files are organized, the prospective researcher

needs to know how to create new data for himself. All of the code you need is contained in the necessaryPrograms folder. So, let's spend some time understanding the steps involved. I have changed my process several times since I started on this project, the most recent code is inside of the acs folder. It is that folder that I will be referencing.

A.2 Creating the Models

The first thing you will need to do is create the model PSFs. First,you will need to modify the infile.XX.list file; it is dependent on the size of the Tiny Tim model. Work with Dr. Stephens to make sure you are using the right numbers in that file. (Or, just use the same one that is being used for the analysis of the actual data)

Second, the input.XX.prim file is also size dependent. There is an important difference between the one used for the actual data and the one used for the simulated data. The actual data models count up from prim.00.psf, while the simulated data models count down from prim.99.psf. Copying to and from an excel spreadsheet is a quick way to change the necessary column.

Third, make sure the bin.f program is using the correct method. Some cameras have special kernals that need to be applied. Lastly, change the file paths in psf.script as needed.

Now that everything is set up, all you need to do is run the psf.script file in the psfModels folder for your filter. The script will open up IRAF, where you need to run wtext @infile.XX.list. The psf.script should do everything else automatically.

A.3 Creating the Data

Now we need to create the simulated binary data. The only thing that should need to change is the infile.XX.list files in the hmodels folder. These are auto-generated by the createFiles.f program. It requires the size of the Tiny Tim file as a command line argument. The input.XX files should be

the same for every camera. The only other thing to check is that you are using the correct bin.f program.

Once everything is set up, all you need is a Tiny Tim file and the createModels.cl IRAF script. To run the script you need to open IRAF and type: cl < createModels.cl. If everything is set up correctly this will automatically generate a series of mod.XX.XX.psf files. These are single star models which we will combine to create binary models.

To create the binary models we also need to know the background values to use. These are stored in the background.txt file. Open the actual data files in IRAF and use imexam to find the background level. Pick three representative values of the noise and standard deviation.

We will also need the conversion from magnitude to flux, which is filter dependent. Work with Dr. Stephens to make sure you have the right equation in the modgen.f program. And store the constant needed for said equation in the fluxConstant.txt file.

A.4 Running the Program

You are now ready to start the actual binary data creation and fitting program. There is a bash script that will do everything automatically for this step as well. The doEverything.script file will create an himages directory, run the modgen.f program to fill the directory with binary data, then run the binary fitting program on it. You will need to make sure you are using the correct binary fitting method for the camera you are analyzing.

To speed things up, I like to run three simultaneous instances of doEverything.script. Each one creates ten himages directories. Since each computer in the astronomy department has four processors, the three instances can run in parallel.

A.5 Analyzing the Results

The doEverything.script will automatically copy the modcompXX.txt file into the results directory. This file contains all the yes/no for each data set. To add up all the files and get a final percentage we need to run the percentage.f program. The source code is in the /data/BDbinaries/Doug/bd0559 folder. The program expects a command line argument that tells it how many modcomp files there are.

Finally, we use a Mathematica notebook to visualize the results and generate the graphs used in this paper. The notebook, called analysis.nb, is in the /data/BDbinaries/Doug/bd0559 folder.

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