

# Accomplishments of Summer 2005

Merek A. Chertkow, California Polytechnic University Pomona

*Advisor: Dr. William Welsh, San Diego State University*

Unlike the other REU students, I was not presented with one data set of which I was to reduce, investigate, and provide conclusions for. Rather, I was posed with a set of problems all of which were aimed at the task helping me develop new skills and gain experiences in the various fields of astronomy. I had to consider data in fundamental ways that were new to me, perform precision CCD photometry with IRAF while performing sanity checks throughout the data manipulation steps, and finally, where applicable, considering possible conclusions or even realizing that what we were investigating requires more time to understand the processes better.

## Introduction

The following is a listing of different project I have worked on this summer.

### I

The first task was to observe the Deep Impact Event through the 1-m telescope at Mt. Laguna Observatory with Dr. Welsh and Dr. Etzel. I gained my first experience in observing and reducing data using IRAF. Once the data were reduced I turned the sequential images into an animated gif which was uploaded to a web presentation page for our observations. This page was cited in *Sky & Telescope*.<sup>4</sup>

### II

We investigated extra solar planet satellites. This required learning about the Roche limit and the Hill Radius (equivalent to the inner Lagrange L1 point radius). We wanted to understand some of the parameters in which a satellite could exist. There is a range in which a satellite can maintain a stable orbit between a Jupiter-like planet and a third object (in this case a star). For the Jupiter-like planet we used TrES-1 and HD209458. The theory and mathematics involved were not too complicated provided one understands what exactly is going on. We later discovered that this type of system is more complicated than we had first expected and so my calculations were just a small step in understanding the parameters of a star, planet and moon system.

See Table 1 for calculated periods of lower range mass satellite similar to Jupiter's Callisto and an upper range mass satellite similar to Earth around the hot-Jupiter extrasolar planets TrES-1, HD209458 and OGLE TR56. Periods were found using equations for rigid body satellite and fluid body satellites<sup>1</sup>. It was not surprising to find that many of the periods were found to be fractions of a day because we know that the real Jupiter moons have similar periods. The periodicity near the Roche limit is independent of the planet being a hot-Jupiter. Where the planets proximity to its star comes into play is at the Hill Radius. If the satellite were to be further than about 1/3 or 1/2 the Hill Radius<sup>3</sup> then it would not remain in a stable orbit. Thus, the maximum period for our calculations yields 1.95 days.

Roche and Lagrange Distances			
	TrES-1	HD 209458	OGLE-TR56
<b>Roche Radius (km)</b>			
<b>Earth-Like</b>			
Rigid body	4.65E +04	4.85E +04	6.21E +04
Fluid body	8.94E +04	9.32E +04	1.19E +05
<b>Callisto-Like</b>			
Rigid body	66769.55	69569.39	89109.60
Fluid body	1.28E +05	1.34E +05	1.71E +05
<b>At Hill Radius (km)</b>			
Hill Radius	3.57E +05	4.00E +05	2.57E +05
1/2 of Hill radius	178291.69	199787.12	128359.82
Period at Roche and Lagrange Distances			
	TrES-1	HD 209458	OGLE-TR56
<b>Period at Roche Radius (hrs)</b>			
<b>Earth-Like</b>			
Rigid body	1.98	1.98	1.98
Fluid body	5.27	5.27	5.27
<b>Callisto-Like</b>			
Rigid body	3.40	3.40	3.40
Fluid body	9.07	9.07	9.07
<b>Period at Hill Radius (hrs)</b>			
1/2 of Hill radius	14.85	16.56	5.88

**Table 1** - Periods of Earth-like and Callisto-like satellites around TrES-1, HD209458, and OGLE-TR56.

We soon realized upon further investigation into this problem that there are many effects the satellite can have upon the system. One, if the satellite is orbiting in the same plain as that of its parent body, then the center of mass will change its apparent velocity relative to the observer and transit can occur at different times or vary within transit. The effect could be a shifting, widening, or shrinking of the width of the transiting light curve. Two, if the satellite orbits out of the orbital plain of the planet, then the center of mass will follow a sinusoidal path – in effect, the transit will wobble in inclination. Third, if the satellite has a large enough radius, it too will block out light from the star. Due to the not-so-simple-motion of the satellite, from Earth’s point of view, these effects will be very difficult to account for. Unfortunately, we did not have time to investigate further.

### III

A quick problem that was posed by Dr. Welsh was the possibility of a “Jumping Jupiter” being thrown into a dense nebular cloud from which it could accrete enough matter to become a brown dwarf. We found an equation for this type of spherical mass accretion from Accretion Power in Astrophysics<sup>1</sup> This question ended up being a rather simple text book problem that any student could have solved, but the point wasn’t in the difficulty of the problem; the point was to answer a question we believe had never been asked before, and whether this process could be a viable form of brown dwarf evolution?

The accretion of mass onto an object traveling through a medium with a given density and speed through the medium given by Frank, King, & Raine

$$\dot{M} \cong 1.4 \times 10^{11} \left( \frac{M}{M_{\oplus}} \right)^2 \left( \frac{\rho(\infty)}{10^{-24}} \right) \left( \frac{c_s(\infty)}{10 \text{ km s}^{-1}} \right) \text{g s}^{-1} \quad \text{eq. 2.32}$$

Where,  $\rho(\infty)$  = density of nebular gas cloud and  $c_s(\infty)$  = sound speed of gas

For a low density nebula,  $\rho(\infty) \approx 10^7$  particles/cm<sup>3</sup>  $\approx 1.66 \times 10^{-17}$  g/cm<sup>3</sup> with  $c_s(\infty) \approx 10$  km/s. The mass of a Jupiter-like planet,  $M = 1.8987 \times 10^{27}$  kg, the mass of the sun  $M_{\odot} = 1.9889 \times 10^{30}$  kg and the mass of a brown dwarf,  $M_B = 0.084 M_{\odot} = 2.5856 \times 10^{28}$  kg. We find,

$$\dot{M} = 2.118 \times 10^9 \text{ kg s}^{-1}$$

Solving for the time it takes a Jupiter-like planet to evolve into a brown dwarf,

$$\frac{M_B - M_J}{\dot{M}} = \frac{2.3957 \times 10^{28} \text{ kg}}{2.118 \times 10^9 \text{ kg s}^{-1}} = 1.131 \times 10^{19} \text{ s}$$

$$1.131 \times 10^{19} \text{ s} = 3.584 \times 10^{11} \text{ years}$$

In laymen's terms, it would take much longer than the age of the universe for this to happen. Although the result proved to be interesting it is obviously not significant – at least we have answered the problem. One can see that even if we considered a more dense nebular cloud or a higher sound speed of the gas the result would not change an amount that would really make a difference.

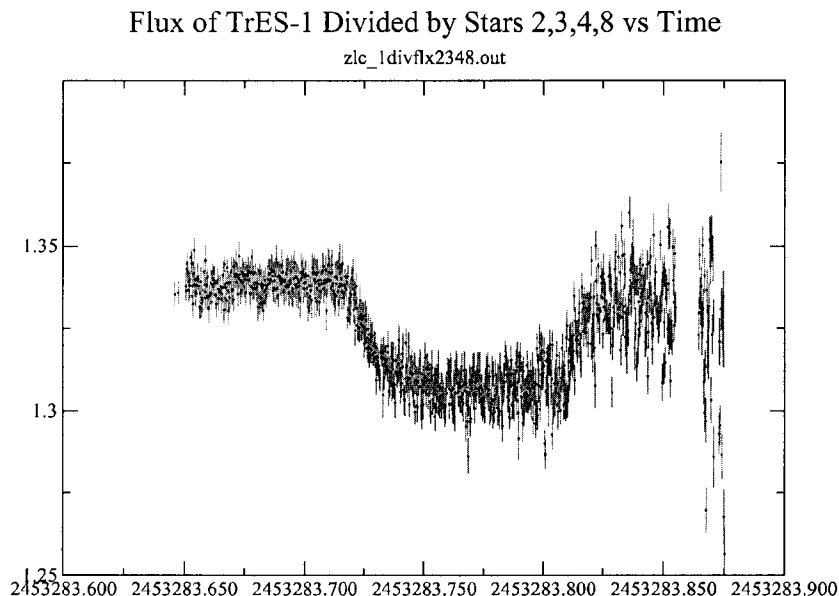
#### IV

Dr. Welsh had observed TrES-1 in 2004 with the 1-m telescope at Mt. Laguna Observatory. I was to reduce this data set using techniques that would provide high-precision photometry aimed to achieve better than 1%. Unlike the Deep Impact project, of which the goal was to produce a high quality animation of the event, our goal with TrES-1 was to obtain very small amplitude of the variations in the data – to obtain as much precision and accuracy as possible. The purpose of working with the data set was to gain expert experience using IRAF, writing FORTRAN programs, and most importantly understanding the data. We did not want to perform a step where we did not know exactly what was happening. Almost every step was accompanied by a sanity check in some way. After reduction we realized our image of TrES-1 is accompanied by two additional stars that bled into the light coming from TrES-1. These stars formed what we call the “Panda structure.” We decided to investigate if these stars were bright enough to affect our calculated transit depth. By using a small enough aperture in the differential photometry process we could neglect the panda structure and then compare our results with a transit in which we included the additional stars.

TrES-1 was observed with the 1-m telescope, using an R filter, with a CCD window of 800x400 and 1024x1024 pixels and plate scale of 0.4"/pixel. This observation took place at Mt. Laguna Observatory on 5 Oct 2005 3:21 through 8:59 UT by W. Welsh using the “CCD2001.” The predicted transit time was 6:25 UT. For calibration, 20 early flat fields (flats), 20 early zero frames (zero(s)), 10 late flats, and 10 late zero images were taken to reduce approximately 980 images of TrES-1. Throughout the observation there were a couple anomalies: there was a dome occultation of a few images. Special attention was paid to the reduction procedures using IRAF to try and insure both precision and accuracy of the analysis of this data set. I computed the CCD readout noise and gain via IRAF's FINDGAIN task. One specific test was to create an early and a late zero master frames which were divided by each other to check for stability of the duration of the observations we found an image with a mean value of 1.007 and standard deviation of  $5.154 \times 10^{-4}$ . CCDPROC was then used to apply the early master zero frame to the early flat field images and the late master frame to the late flat field images. From these images FLATCOMBINE created one early master flat and one late master flat. The early master flat was divided by the late master flat producing an image with a mean value of

0.9888 and standard deviation of 0.00718. The normalized master flats were applied to the images. We knew that the normalized master flat created using all of zero and flat field frames would work to reduce the image frames, but the question was how well? To answer this, the “m” command was used in IMEXAM to find a statistics box on four corners of three different star field images each at a different stage in the reduction process. The three stages were: a raw image, a bias reduced image, and a bias reduced that has been divided by the normalized master flat. In each test, the image became significantly flatter with respect to its mean value. A raw image would drop from a tilt value of about 10 counts across the CCD to a tilt of 1 or 2 counts.

I working with the TrES-1 star field we had to be sure beforehand that the stars in our field were not variable and were safe to use as comparisons. So, we plotted light curves of each star and found that they are all very level and do not deviate from their median by more than 0.4% (in the worst case) prior to the gap in the light curve. We ran several version of the differential FORTRAN code and found that the smallest rms of the flat out-of-transit part of a light curve of TrES-1 is 0.26% rms. if we used comparison stars 2, 3, 4, and 8 (see Fig. 1). We have reached much better than 1% photometry. The average flux value before transit is 1.3385, and mid-transit is 1.3064. This gives a transit depth of 2.86%.



**Fig. 1.** Differential light curve of TrES-1 (star 1) using comparison stars 2, 3, 4, and 8. The large scatter is due to very high airmass. Note: time in HJD.

When we compared the flux of the TrES-1 “panda formation” we found that using an aperture of 5 pixels excluded 1.48% of the flux found by using aperture 24 pixels. This means that if the panda formation did not exist the 2.86% transit depth would be larger by 1.48%. In total, that is a 0.035% change in the transit depth. As stated earlier, the scatter about the light curve is 0.250%, which is significantly more than 0.035%. Therefore, the panda formation has a negligible affect on the real light curve level, and no revision of the planet’s radius is required.

## V

My second observation experience was again at the 1-m telescope at the Mt. Laguna Observatory on 8 July 2005 where we observed a transit of HD209458. Because of the conditions and

rise time of HD209458 we were only able to observe starting from mid-transit. With this data set I was to perform the same type of precision CCD photometry as I had with TrES-1 – again performing sanity checks along the way to ensure that our final light curve was accurate. If we are able to obtain positive results for this data and find a transit then this data set will go on to become part of a larger study of HD209458 currently underway, searching for satellites or other planets via mid-eclipse timing changes.

To date, we are stumped by our results. We know that we should expect to see only about half of the transit in the beginning of our light curve. Using Robert Wittenmyer's best ephemeris we expect to find a transit depth of 2.8%. Our best out of transit rms is 0.67%. Although this is high, we still expect to be able to pick out the egress of transit within the light curve. Again, we have reached better than 1% photometry, but our results are inconclusive. We currently believe that we have captured part of this transit, but critical data analysis is still underway to understand why there is so much scatter early in the light curve – see Fig 2.

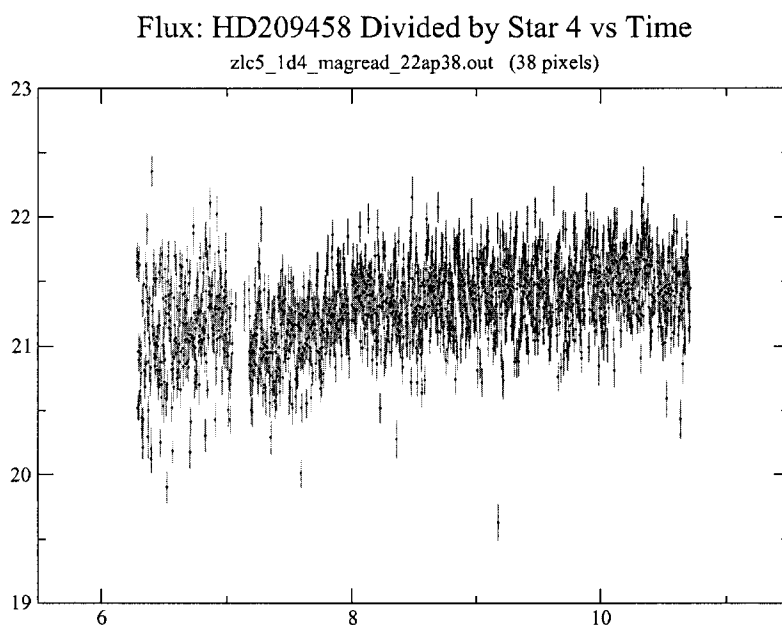


Fig. 2. Differential light curve of HD209458 (star 1) divided by star 4. Note: time in UT.

## VI

Dr. Welsh had also observed additional transits of TrES-1 and HD209458 with the newly re-assembled 24-inch telescope at Mt. Laguna Observatory. These two new sets came with their own boatloads of idiosyncratic problems which one has to become familiar with in order to properly reduce. I had begun to work with the 24-inch HD data set and had almost produced a light curve, but due to a lack of time, I was not able to finish reducing the data.

## Conclusion

I am now comfortable with performing high precision CCD photometry, working with Linux, and writing FORTRAN codes to perform mathematical operations – all of which I would have been completely lost or uncomfortable to work on my own with. For many of the REU students this has been a summer to obtain results with a single data set in hopes of publishing their results – this was

not the case for me. I investigated a wide range of topics; I observed; I reduced and calibrated data; and I did some theoretical calculations. Most importantly, I believe I have grown and gained an invaluable skill in recognizing the relationship between sets of data and how to approach new information I am just introduced to. As a physics student I am always posed with new problems and concepts, but I have never been given an ensemble of information and had to deal with it like I have this summer.

### Acknowledgements

Dr. Jerry Orosz Department of Astronomy, San Diego State University.

Dr. Eric Sandquist Department of Astronomy, San Diego State University.

### References:

1. Frank, King, & Raine. Accretion Power in Astrophysics. Cambridge, 1992
2. Hill sphere: Information From Answers.com. Wikipedia. July 15, 2005  
<<http://www.answers.com/Hill%20sphere>>
3. Roche limit: Definition and Much More From Answers.com. Wikipedia. July 15, 2005  
<<http://www.answers.com/Roche%20limit>>
4. Alan M. MacRobert. Sky and Telescope - The Comet After Deep Impact. Sky and Telescope August 18, 2005  
<[http://skyandtelescope.com/observing/article\\_1540\\_1.asp](http://skyandtelescope.com/observing/article_1540_1.asp)>