MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF EARTH, ATMOSPHERIC AND PLANETARY SCIENCES

Summer 2010 UROP Project Report

Extrasolar Planet Transits

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Abstract

Various Extrasolar planet transits were observed on 14 inch telescopes from Wallace Astrophysical Observatory in Westford, MA. Photometry was performed on these data sets that were calibrated using the software IRAF prior to the photometry. 7 successful light curves were generated for the exoplanets WASP-2b, TrES-3, TrES-1 and XO-1b. Fitting was then performed on the good light curves. The project allowed determining certain properties of the exoplanets observed and analyzed successfully.

Acknowledgments

I'd like to thank Jim Elliot for giving me the opportunity to work on this project, Mike Person for his time, support and feedback, Tim Brother for teaching me how to operate the telescopes at Wallace Observatory, Elisabeth Adams for guiding me, teaching me and answering my many questions throughout the project, my project partner Stephanie Gibson and the other UROP 2010 undergraduates for their help and support.

Observation

I- Introduction

An extrasolar planet (exoplanet) is a planet that orbits a star outside the solar system. There are various methods for detecting exoplanets. Each method makes it possible to determine certain properties of the planet. It is possible to determine the radius and other properties of the planet through the transit method. These properties include the period and transit mid-time of the exoplanet. A transit happens when a planet passes in front of its parent star's disk.

II- Procedure

The decision to go to Wallace in order to observe a transit was based on the properties of the transit. Exoplanet transits whose central star was too dim were not attempted, as well as transits that were too shallow (of a depth lower than 1 %) to be observed from Wallace.
Several transit observations were attempted. This resulted in more than 17 raw data sets all of which were observed on 14 inch telescopes at Wallace Observatory. All of the transits were observed using the R filter. Calibration frames (FLATs, BIASEs and DARKs) were taken on most of the observation nights. Skyflat images were taken during twilight. Usually, two sets of DARK frames were taken. One set had an exposure time equal to that of the SCIENCE images, and the other equal to the exposure time of the FLAT field images.

III- Difficulties

More than half of the raw data taken was not useful because of several limitations. Some of the known ones include bad telescope mount tracking, cloudy weather, and moon glare near the target. The 14 inch telescope resolution made it impossible to see certain fainter stars near the target star. This occasionally made it difficult to recognize the target star in the frame when the finder charts used showed the comparison stars that weren't visible in the frame, making the patterns hard to recognize.

Calibration

In order to correct the errors in the data, calibration must be performed. Calibration was performed using IRAF. DARK frames of similar exposure times were combined using the *imcombine* function. The resulting dark frame is then subtracted from FLATs and SCIENCE images of the same exposure time using the function *imarith*. The DARK subtracted FLATs are then combined. The combined FLAT is then normalized by dividing it by its mode value using the function *imarith*. The DARK subtracted SCIENCE images are then divided by the normalized FLAT.
BIAS frames must be used if there are no matching DARKs for either the SCIENCE images or the FLATs. The BIASEs are either used in exposure scaling the DARK frames, or in order to be subtracted from the FLAT frames. BIAS frame calibration was never performed on any of the data sets as needed DARKs were available.
For some more details about the frames used for calibration of each individual set, see table A below.

TABLE A

Transit	Transit Date	Frame Type	Exposure Time	Meridian Frame
TrES-1	7/27/2010	SCIENCE	90	25
		FLAT	1.5	
		DARK	90, 1.5	
TrES-3	7/18/2010	SCIENCE	90	None
		FLAT	2	
		DARK	90, 2	
TrES-3	7/22/2010	SCIENCE	90	50
		FLAT	3.5	
		DARK	90, 3.5	
WASP-2b	6/19/2010	SCIENCE	90	None
		FLAT*	20	
		DARK	90 , 20*	
WASP-2b	7/30/2010	SCIENCE	90	95
		FLAT*	1.5	
		DARK*	90, 1.5	
XO-1b	6/21/2010	SCIENCE	60, 90	30
		FLAT*	20	
		DARK	60, 90,	
XO-1b	6/29/2010	SCIENCE	60	None
		FLAT	50	
		DARK	60	

* The Flat frames used for the calibration of this set were taken on 07/15/2010.
* These 20 seconds exposure Dark Frames were taken on the 07/15/2010.
* The Flat frames used for the calibration of this set were taken on 07/27/2010.
* The Dark frames used for the calibration of this set were taken on 07/27/2010.

Photometry

Photometry is a technique of measuring the flux of an object. Differential photometry was performed on the data in order to determine the change in flux of the target star over a time that ranges from before the transit to after the transit. The photometry was performed using IRAF and a *mathematica* pipeline written by Dr. Elisabeth Adams.
The centering box size, the reduced data path and other initial settings are entered manually in the notebook. An *all* list containing all the frame names is created in IRAF. After running some of the first notebook sections, photometry is done on the target star and comparison stars by running the *phot* task in interactive mode in IRAF. An output file (template.txt) is generated and saved. The few following notebook sections are then evaluated. The notebook goes through all of the frames following the target star and the comparison stars. During this step, the notebook might output errors for several reasons. These errors can be fixed by editing the settings in one of the early sections of the notebook.

The notebook will indicate errors for certain frames if the target star or comparison stars are too close to the edge of the centering box. This can usually be fixed by changing the size of the centering box, or by choosing new comparison stars. The notebook will also output errors if it encounters a bad frame. This can be fixed by deleting the bad frame from the *all* list. If the errors are caused by the stars moving too fast between two consecutive frames, a jump must be indicated manually along with the new x and y positions of the star. A jump must also be indicated for the frame following the meridian flip (if there is one). The notebook is evaluated again and the process of editing settings is repeated until there are no errors left.

Aperture photometry is performed on the frames by running the *phot* task again in IRAF, but this time in batch mode (interactive mode off). The later sections of the notebook are then evaluated. Once the notebook outputs the light curves, the best aperture size is entered manually. The best aperture can be determined visually by looking at the different aperture light curves. It can also be known through standard deviation during the pre and post transit baseline. The best aperture is the one with the lowest standard deviation. In order to optimize the light curve, the frame numbers of bad frames are entered manually (bad frames generate points inconsistent with the rest of the light curve). The numbers of the comparison stars desired to be used (certain comparison stars don't generate good light curves) are entered as well. The light curve is then plotted again. If the light curve is still not good enough, one can choose to detrend it. Detrending is done by scaling the light curve plot by the slope of a certain quantity such as airmass, the x or the y positions against time. The final light curve is exported to disk. For light curves generated, see appendices A-D.

Fitting

Light curve fitting (least squares fit) was performed on the good quality light curves in order to determine the properties of the exoplanets. The fitting was also done in a *mathematica* pipeline. The paths to the light curves are entered manually in the notebook. The number of the first good frame and the midtime frame are entered manually. The notebook uses these two settings to estimate the scale and midtime of the transits. Two limb darkening coefficients (u and v) are entered. Limb Darkening is defined as the observed decrease in the intensity of the brightness of a star as one moves through the star's disk from the center to the limb (edge). The filter used during the observation must also be specified. Other parameters needed for the least squares fit include the impact parameter and transit midtime. Individual and joint fits were made for all the good light curves, with the exception of the TrES-1 transit, as we only observed it successfully once. The fitting procedure resulted in several figures (O-C and fit figures) as well as several values. For figures see Appendices A-D. For values see results on the next page.

Results

Table B: TrES-1

Parameter	Mean	SD	Median
Global Radius Ratio	0.14824	0.00404044	0.147648
Global Inclination	87.3392	1.50125	87.3107
Global a/R*	8.84278	0.854063	8.94358
Impact Parameter	0.388698	0.189821	0.420114
Duration	10086.8	461.715	10003.3

Table C: TrES-3

Parameter	Mean	SD	Median
Global Radius Ratio	0.21221	0.0629036	0.17574
Global Inclination	80.6775	1.75374	81.2418
Global a/R*	5.64088	0.419731	5.61011
Impact Parameter	0.901691	0.108426	0.854695
Duration	5227.89	211.72	5233.08

Table D: WASP-2b

Parameter	Mean	SD	Median
Global Radius Ratio	0.2215	0.0989634	0.181854
Global Inclination	79.981	1.73788	80.3115
Global a/R*	5.6692	0.317591	5.61523
Impact Parameter	0.9787	0.131201	0.93703
Duration	7730.3	273.559	7741.13

Table E: XO-1b

Parameter	Mean	SD	Median
Global Radius Ratio	0.137754	0.00197397	0.137603
Global Inclination	88.9523	0.738474	89.0801
Global a/R*	12.1492	0.57702	12.2646
Impact Parameter	0.215935	0.142378	0.198121
Duration	9908.81	284.974	9877.06

APPENDIX A: TrES-1

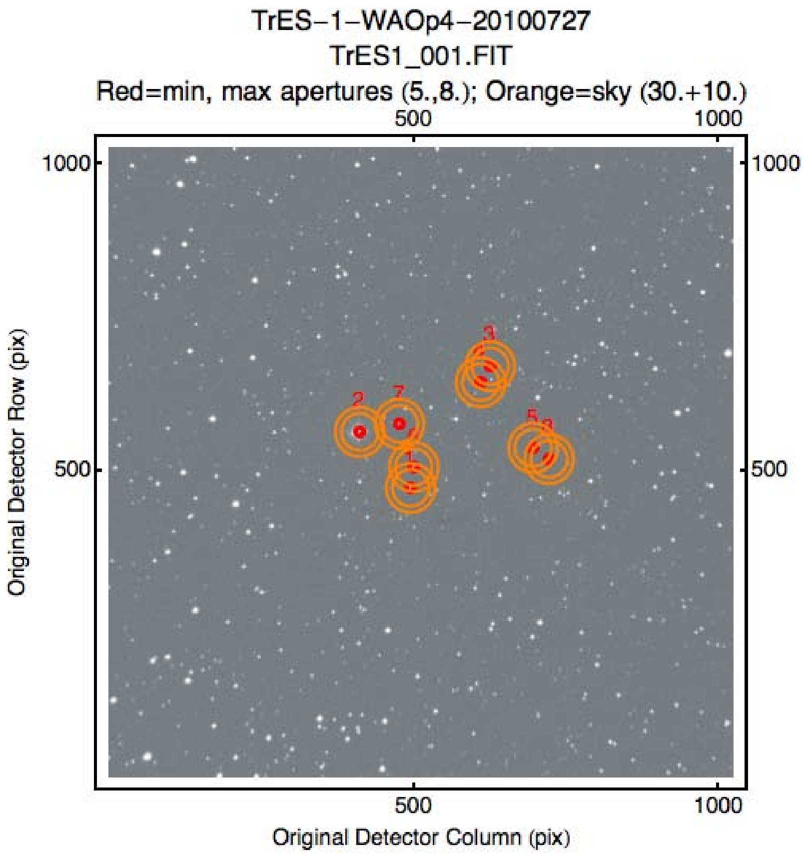

Figure A-1: TrES-1 frame taken on 07/27/2010. The frame is open in astronomical imaging application DS9. The target star is labeled 1. Not all of the comparison stars shown were used for photometry.

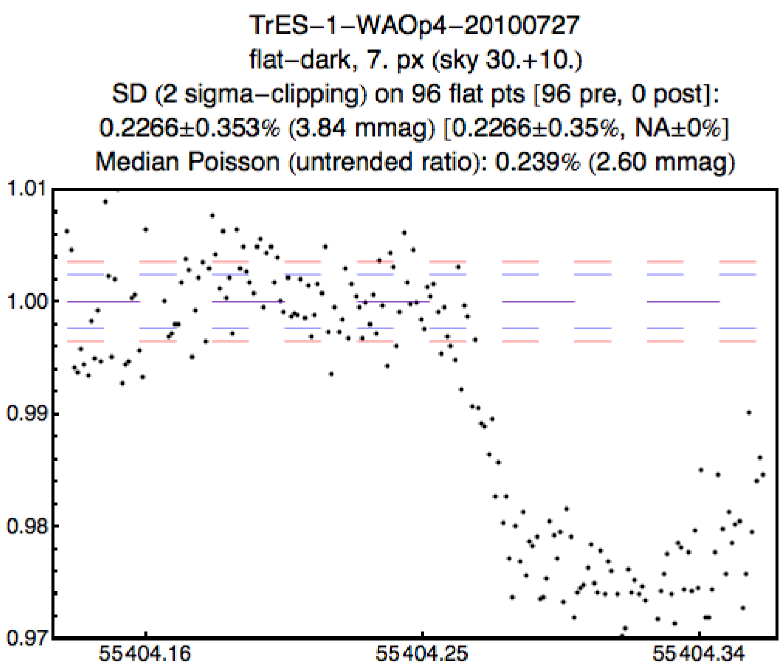

Figure A-2: Light curve generated using comparison stars 3, 4, 5 and 7.

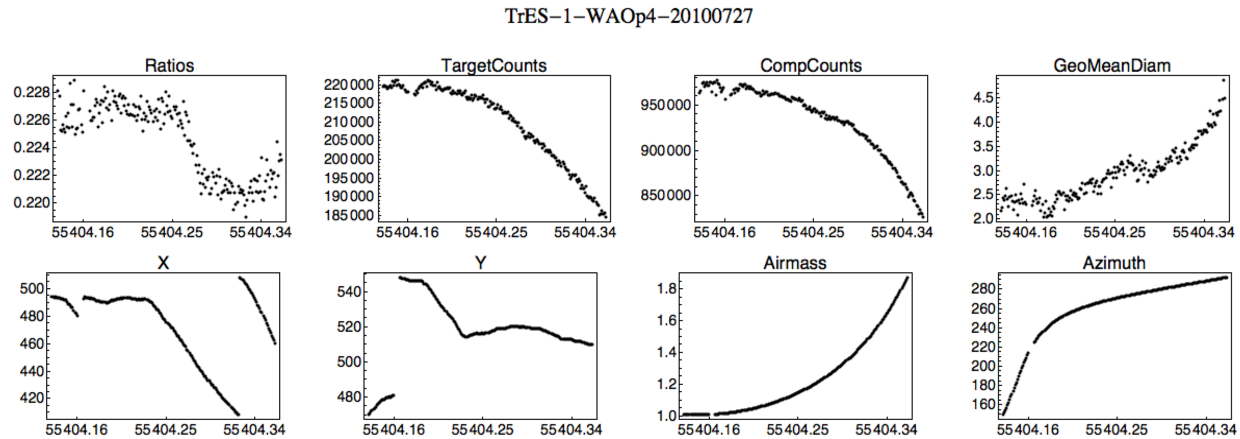

Figure A-3: Other quantities. CompCounts represents the flux of all the comparison stars used for photometry. GeoMeanDiam represents the seeing.

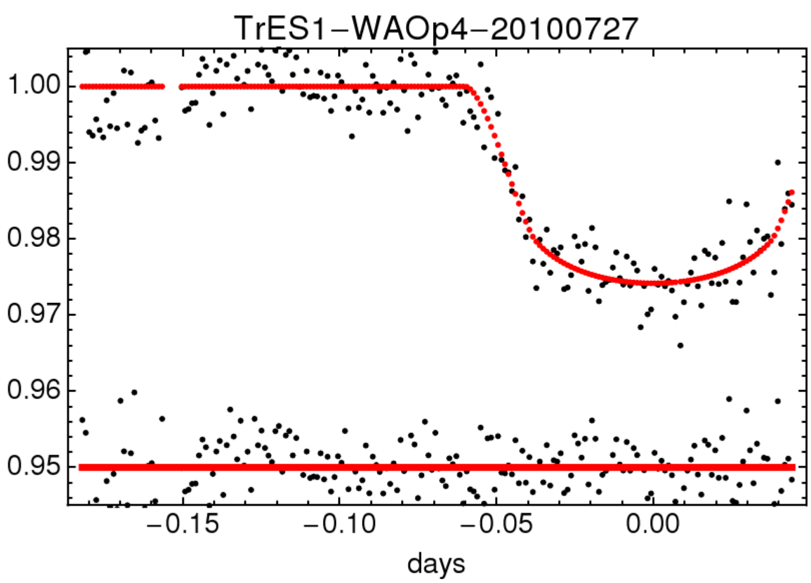

Figure A-4: The top colored line represents a model light curve that resulted from an individual fit. The residuals are plotted below.

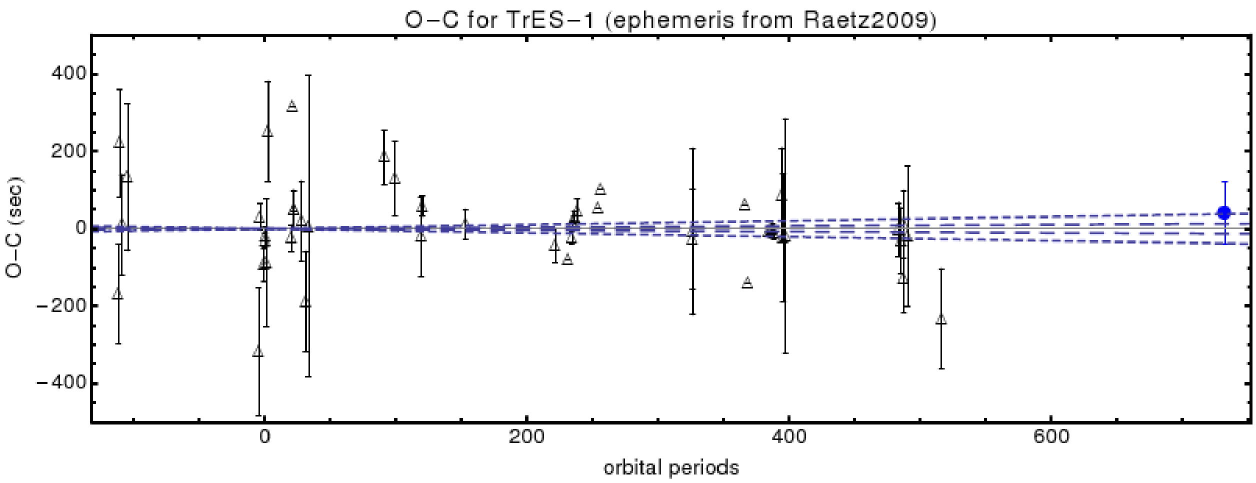

Figure A-5: The blue circle represents the midtime of the individual fit from figure A-4. The triangles are literature midtimes from Raetz2009. The vertical lines represent error bars.

APPENDIX B: TrES-3

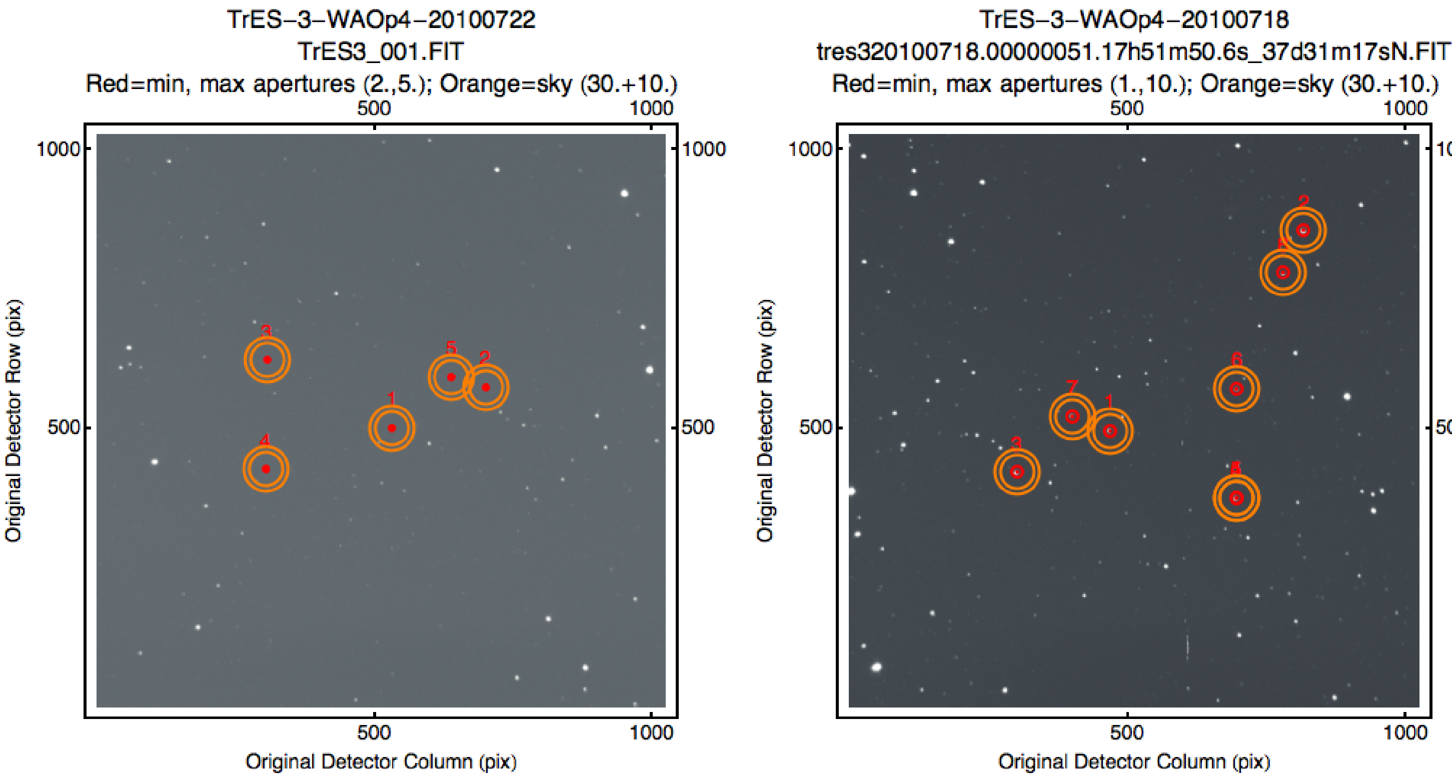

Figure B-1: Two TrES-3 frames taken on two different nights. The frames are open in astronomical imaging application DS9. The target star in both frames is labeled 1. Not all of the comparison stars shown above were used for photometry.

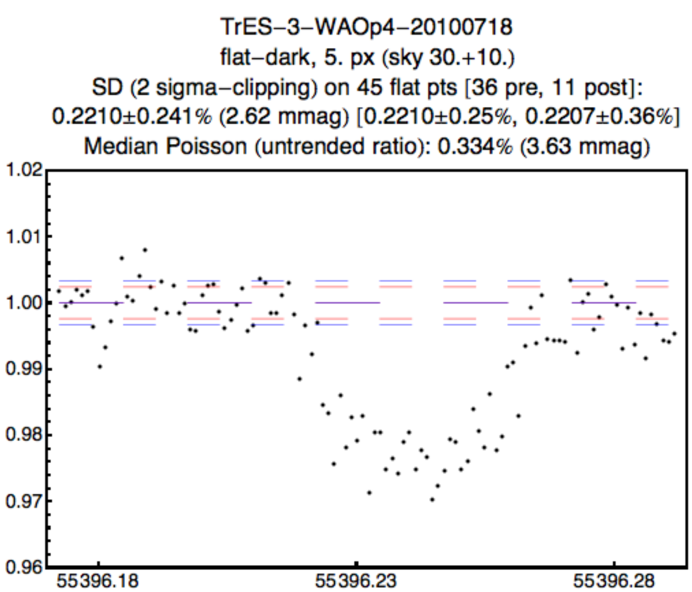

Figure B-2: Light curve generated using comparison stars 3, 4, 5 and 7. The red dashed line indicates Poisson noise.

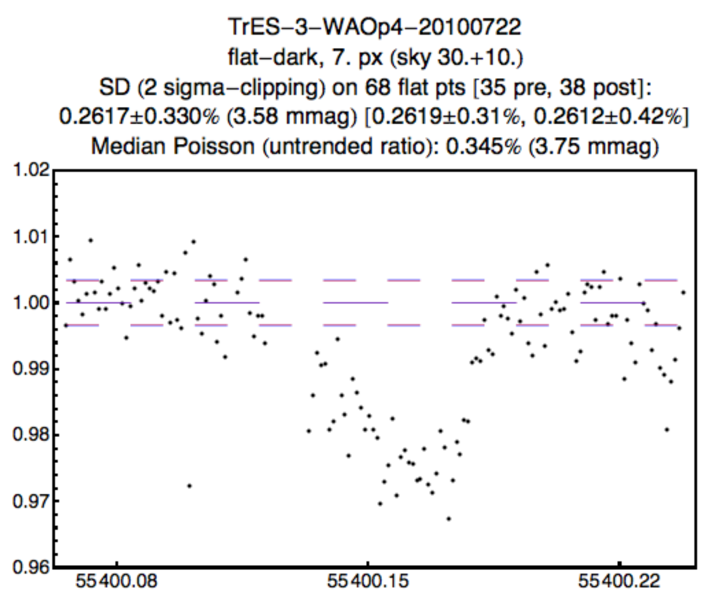

Figure B-3: Light curve generated using comparison stars 2, 3, 4 and 5.

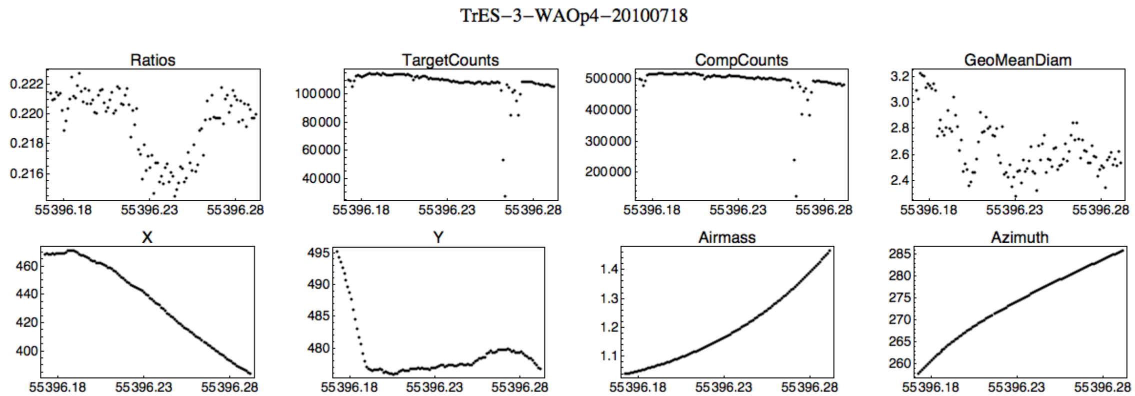

Figure B-4: Other quantities. CompCounts represents the flux of all the comparison stars used for photometry. GeoMeanDiam represents the seeing.

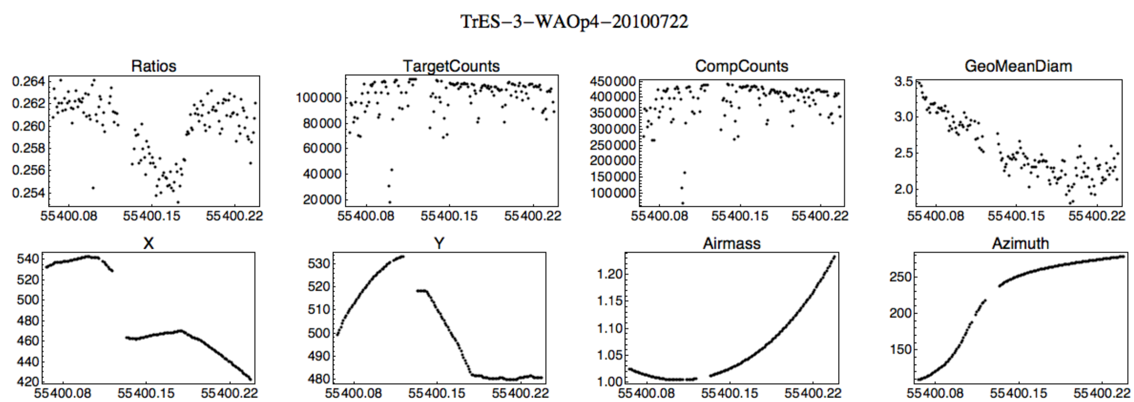

Figure B-5: Other quantities. CompCounts represents the flux of all the comparison stars used for photometry. GeoMeanDiam represents the seeing.

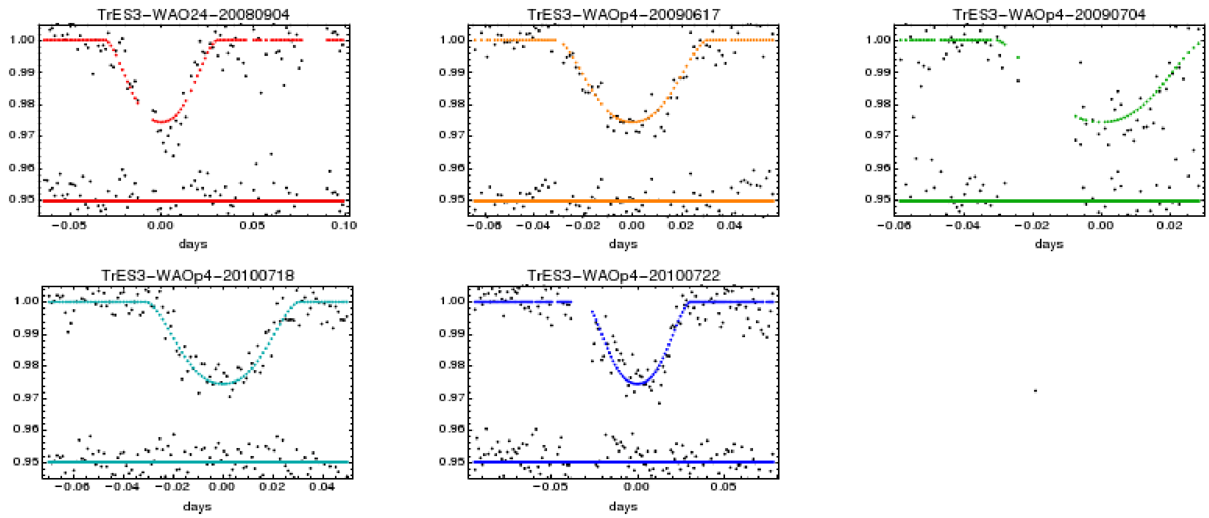

Figure B-6: The top colored lines represent model light curves that resulted from a joint fit. The residuals are plotted below. The 2008 transits were observed by Matthew Lockhart. The 2009 transits were observed by Caroline Morley. Fakhri S. Zahedy observed the transit of 07/18/2010.

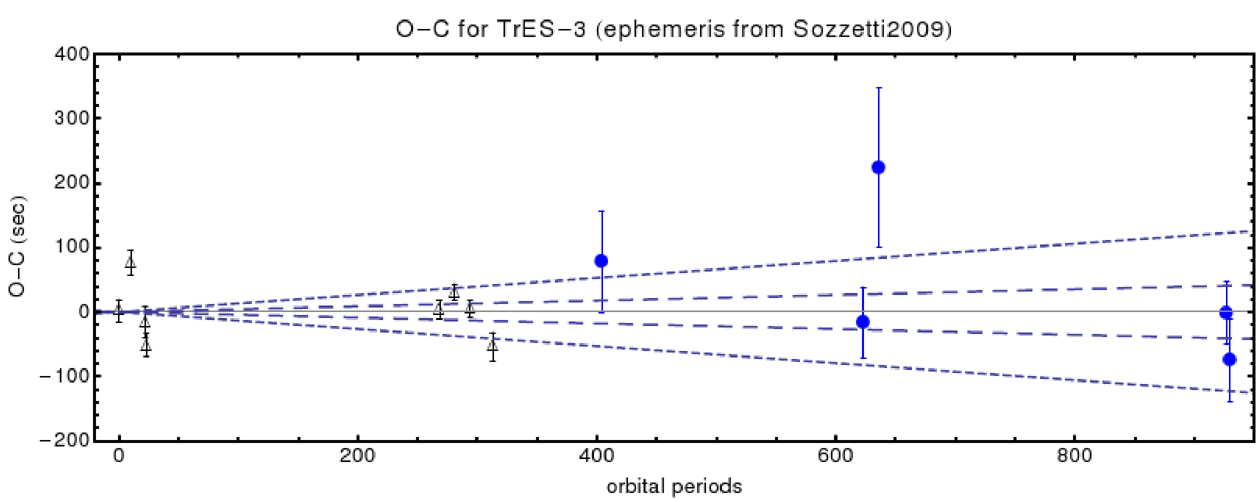

Figure B-7: The blue circles represent midtimes of the joint fit from figure B-6. The triangles are literature midtimes from Sozzetti2009. The vertical lines represent error bars.

APPENDIX C: WASP-2b

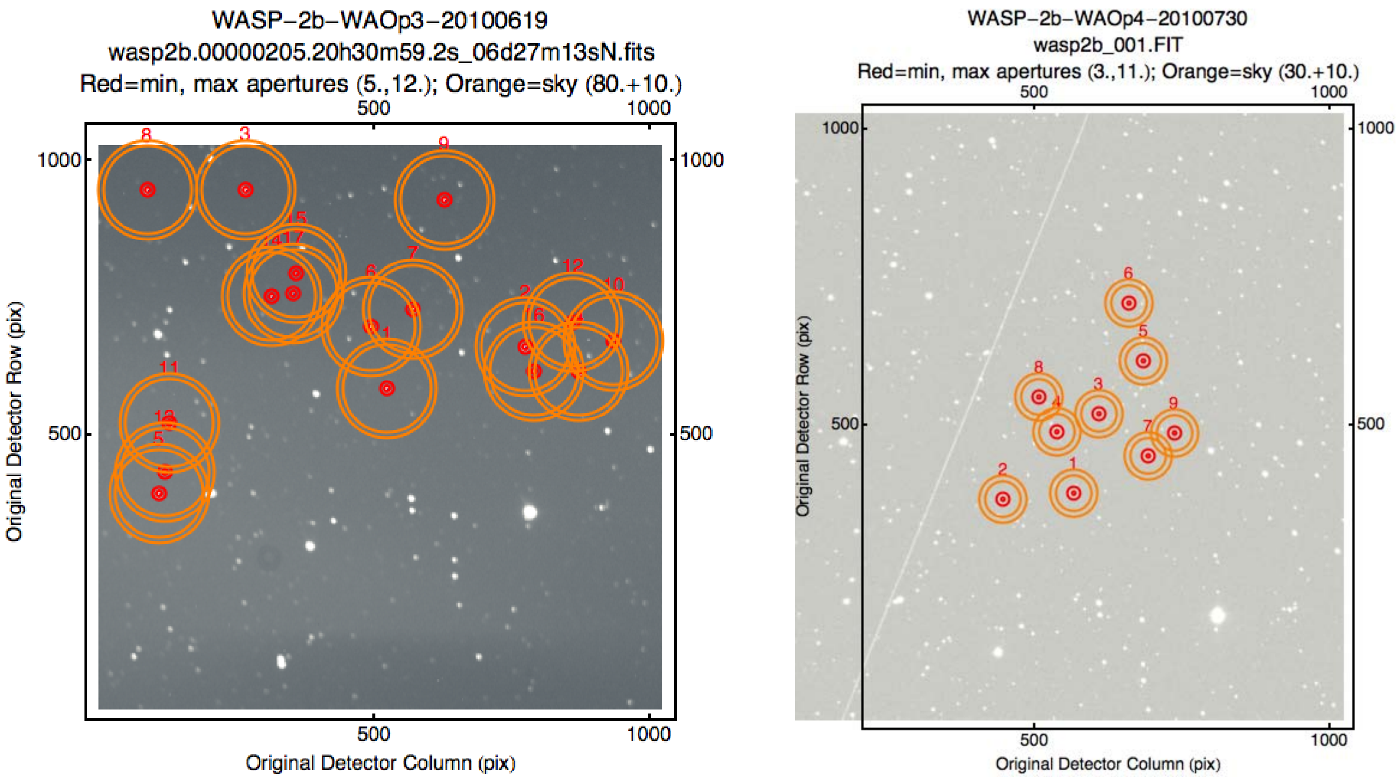

Figure C-1: Two WASP-2b frames taken on two different nights. The frames are open in astronomical imaging application DS9. The target star in both frames is labeled 1. Not all of the comparison stars shown above were used for photometry.

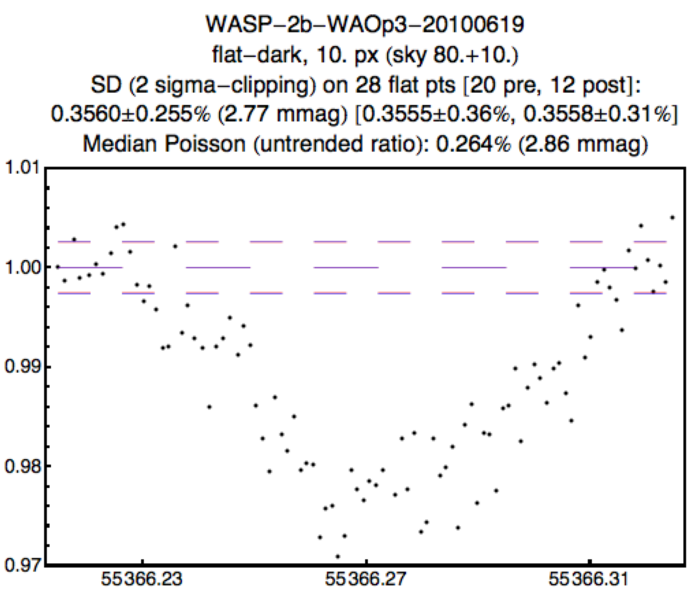

Figure C-2: Light curve generated using comparison stars 2, 4 and 6. This light curve was detrended given that it had a slope proportional to the airmass. The slope is of a value of roughly -0.0031.

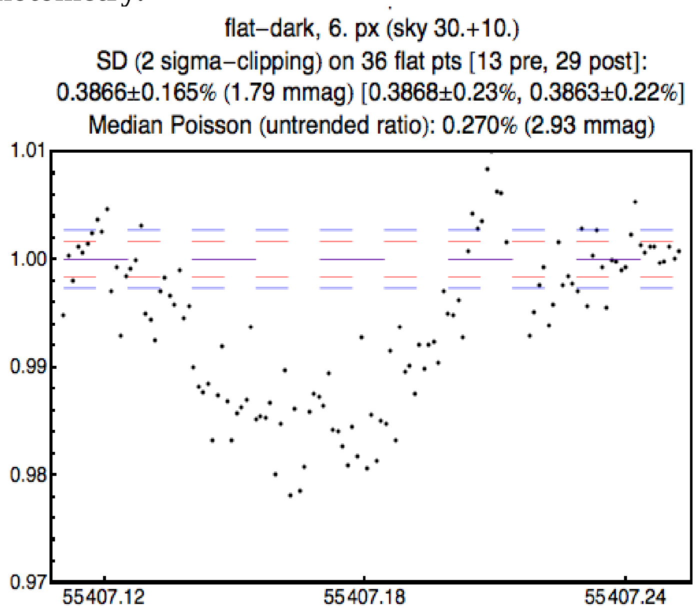

Figure C-3: Light curve generated using comparison stars 7, 8 and 9. This light curve was detrended given that it had a slope proportional to time. The slope is of a value of roughly -0.0374.

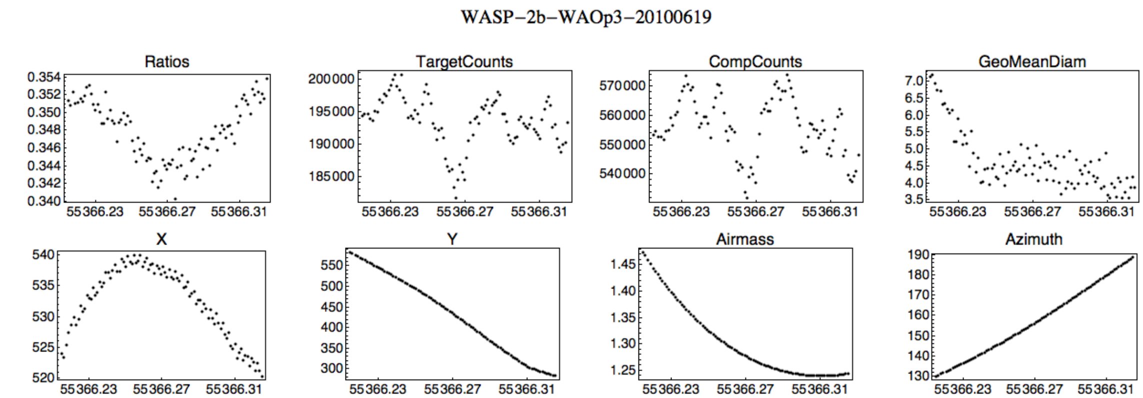

Figure C-4: Other quantities. CompCounts represents the flux of all the comparison stars used for photometry. GeoMeanDiam represents the seeing.

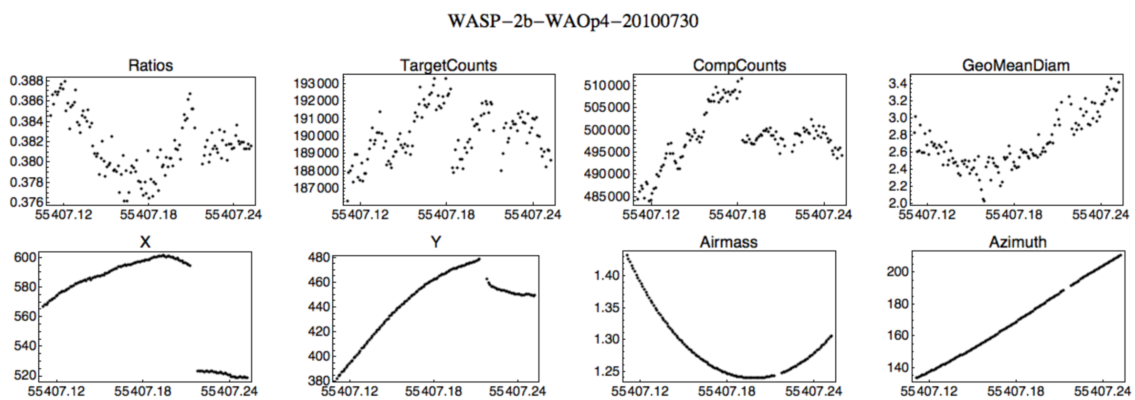

Figure C-5: Other quantities. CompCounts represents the flux of all the comparison stars used for photometry. GeoMeanDiam represents the seeing.

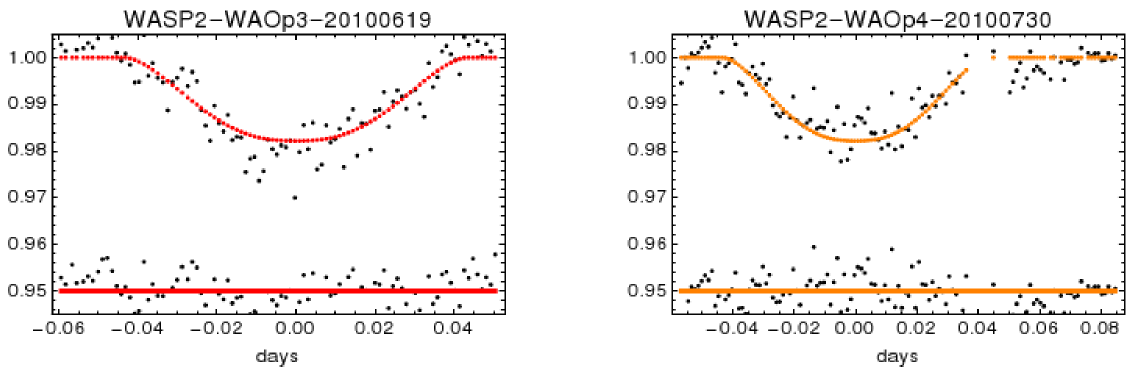

Figure C-6: The top colored lines represent model light curves that resulted from a joint fit. The residuals are plotted below.

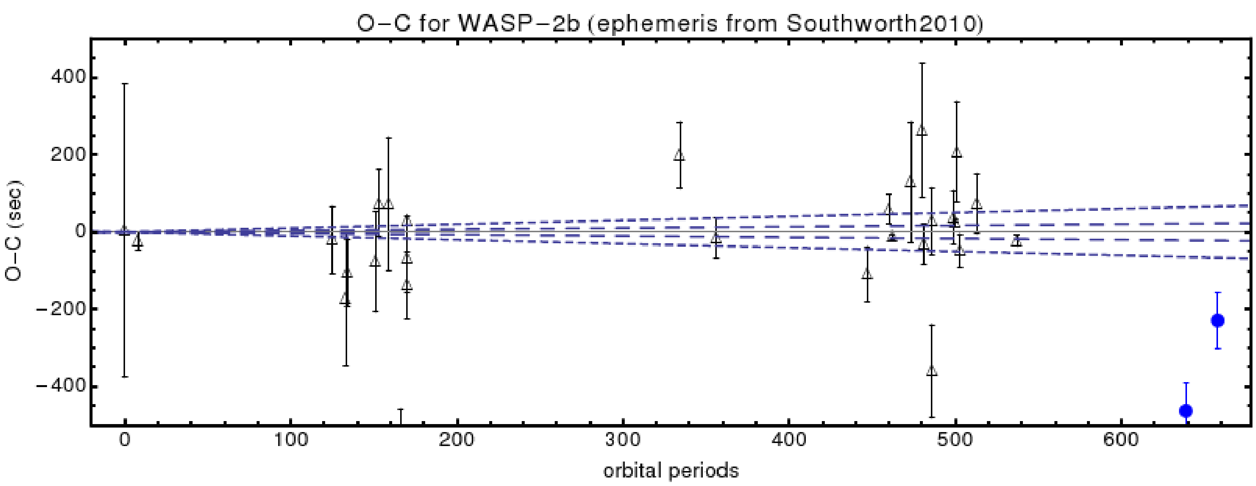

Figure C-7: The blue circles represent midtimes of the joint fit from figure C-6. The triangles are literature midtimes from Southworth2010. The vertical lines represent error bars. The midtimes of the joint fit don't agree with the literature midtimes for unknown reasons.

APPENDIX D: XO-1b

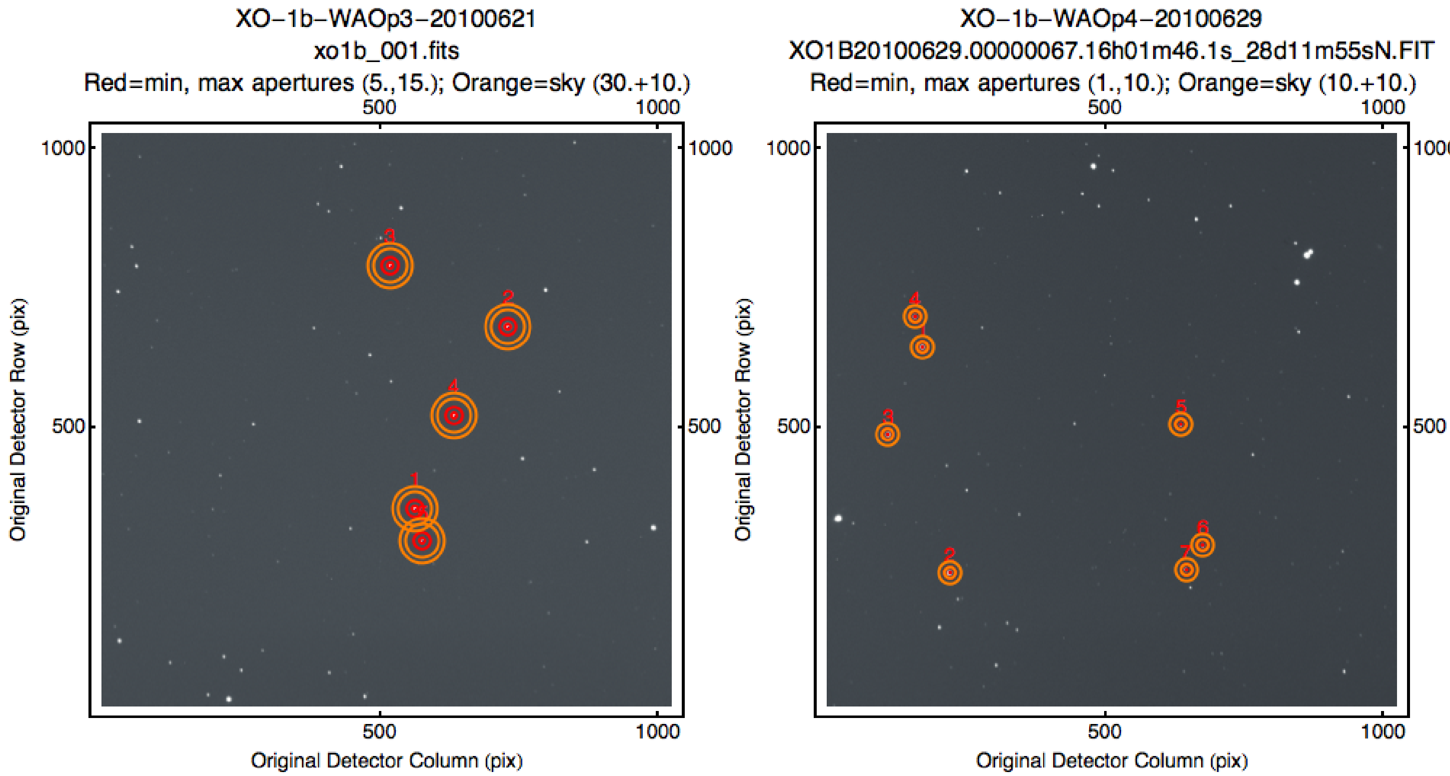

Figure D-1: Two XO-1b frames taken on two different nights. The frames are open in astronomical imaging application DS9. The target star in both frames is labeled 1. Not all of the comparison stars shown above were used for photometry.

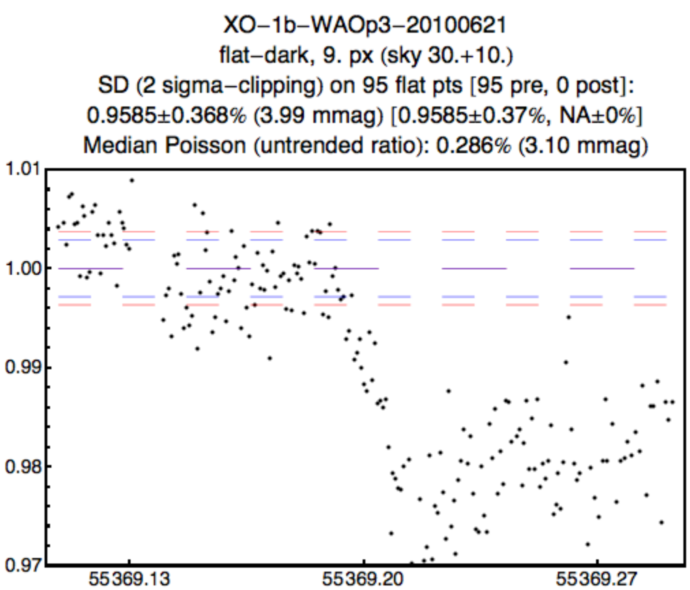

Figure D-2: Light curve generated using comparison stars 4 and 5.

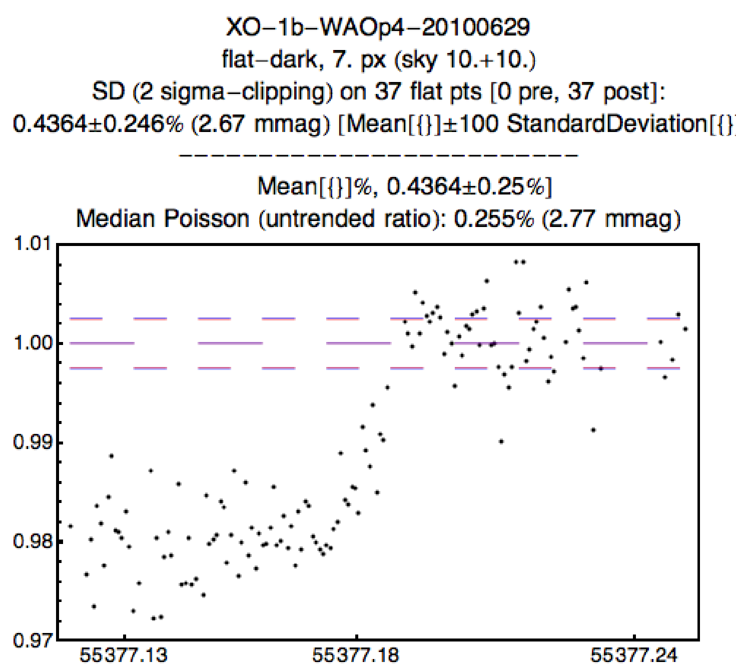

Figure D-3: Light curve generated using comparison stars 2, 3, 4 and 5.

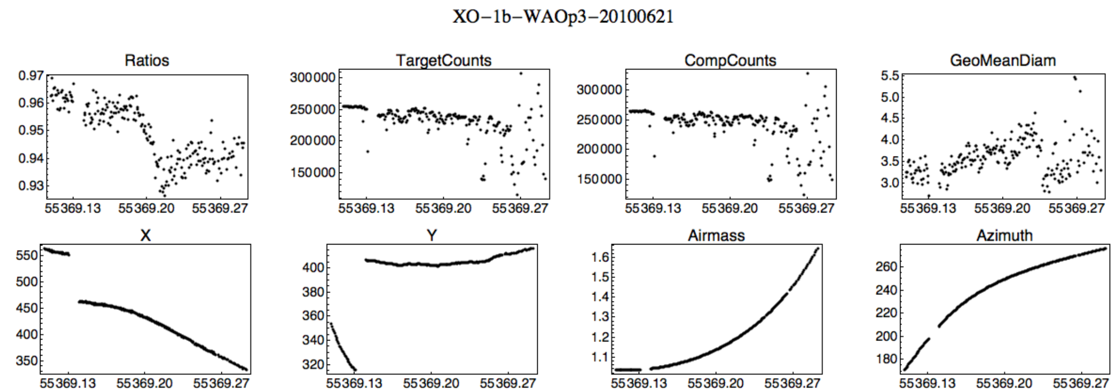

Figure D- 4: Other quantities. CompCounts represents the flux of all the comparison stars used for photometry. GeoMeanDiam represents the seeing.

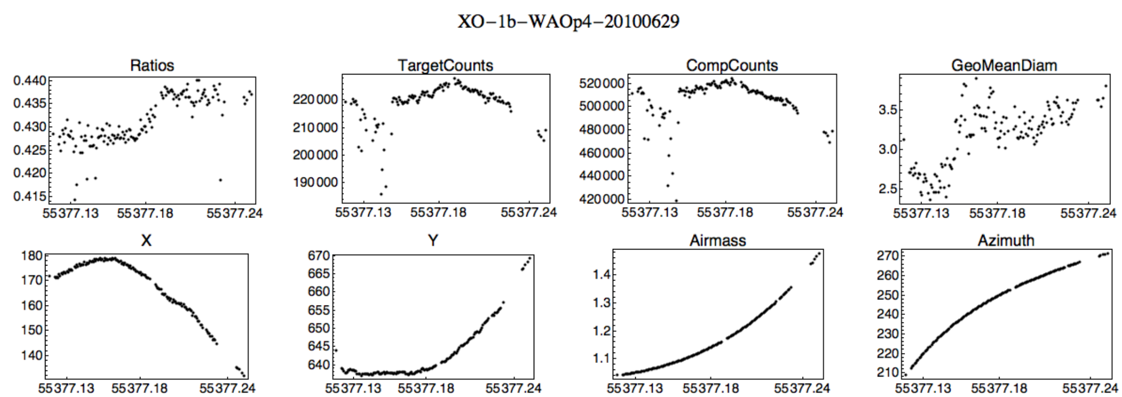

Figure D- 5: Other quantities. CompCounts represents the flux of all the comparison stars used for photometry. GeoMeanDiam represents the seeing.

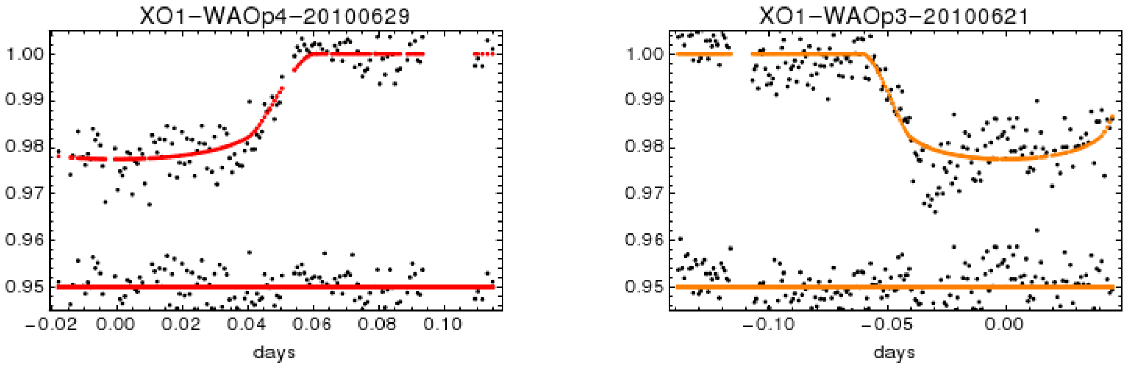

Figure D-6: The top colored lines represent model light curves that resulted from a joint fit. The residuals are plotted below. The 06/21/2010 transit was observed with the help of Fakhri S. Zahedy. The 06/29/2010 transit was observed by Fakhri S. Zahedy.

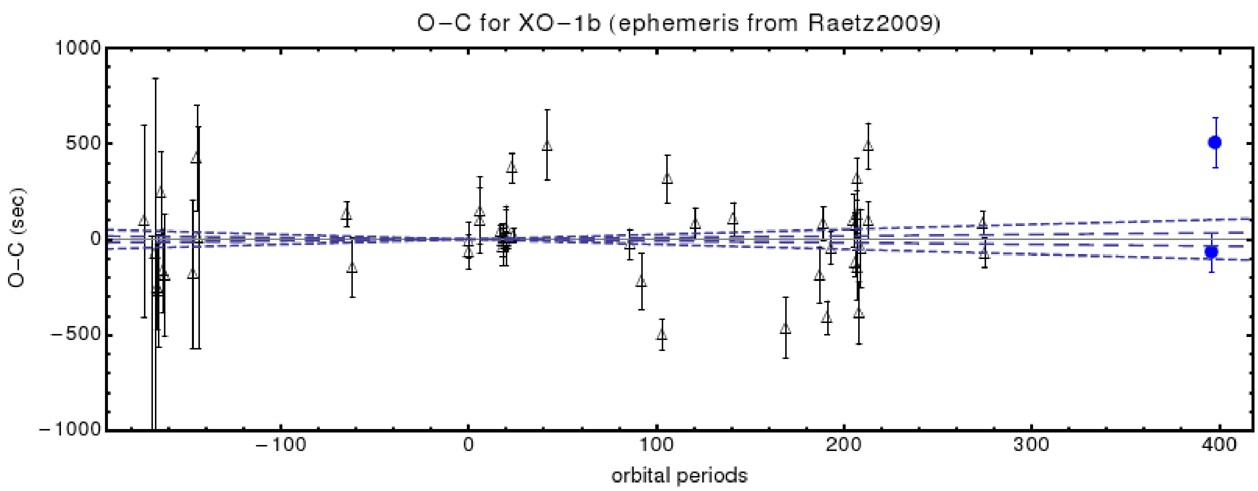

Figure D-7: The blue circles represent midtimes of the joint fit from figure D-6. The triangles are literature midtimes from Raetz2009. The vertical lines represent error bars.

References

Caroline V. Morley. Measuring Transit Timing Variations of Exoplanets using Small Telescopes. Senior Thesis, Massachusetts Institute of Technology, May 2010.

Matthew Lockhart. A Transit-Timing Variation Study of the Extrasolar Planet TrES-3. Master of Science thesis, Massachusetts Institute of Technology, June 2009.