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Constraining the Parameters of Six Known Transiting Exoplanets

Mackenzie Lee Jones
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CONSTRAINING THE PARAMETERS
OF SIX KNOWN TRANSITING EXOPLANETS

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MACKENZIE LEE JONES
APRIL 2012
ABSTRACT

We present two new transits of GJ-1214b, five of TrES-1b, two of XO-2b, and one each of TrES-3b, WASP-16b and WASP-36b. These observations were made with multiple observatories including IRTF-MORIS, Butler University’s Holcomb Observatory, SARA-KPNO, and SARA-CTIO. Due to poor conditions and a lack of good comparison stars within the field of view, the parameter values for the radius ratio, inclination, and orbital distance, found for GJ-1214b are not reliable. The timing values, while still suspect, suggest consistency with the current ephemeris. After further analysis, the radius ratio we found for TrES-1b in Sloan r' is $0.0.13501 \pm 0.00011$, which differs by $3\sigma$ from the Winn et al. (2007) value in z'. A possible cause for this inconsistency is wavelength variation by depth. The other parameters found for TrES-1b were consistent with the Winn et al. (2007) values. In the timing analysis, TrES-1b demonstrated a trend which could suggest an incorrect ephemeris. The radius ratio, inclination, orbital distance, etc., found for TrES-3b were consistent with previous values, which can be attributed to smooth data from good observational conditions and a bright comparison star. Likewise, the values found for WASP-16b deviated very little from previous literature. The parameter values for XO-2b and WASP-36b were consistent with previously published values with the exception of their radius ratios. Both TrES-3b and XO-2b demonstrated consistent timing values, while the lack of observations of WASP-16b and WASP-36b caused the respective timing analyses to be inconclusive.
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1. Introduction

Exoplanets are still a relatively new area of astronomy. The first of these discoveries was made only twenty years ago by Wolszczan & Frail (1992) when they discovered a planet orbiting a pulsar after forming from the debris of a supernova. A few years later, Mayor & Queloz (1995) discovered the first planet orbiting a main sequence star, 51 Pegasi, by observing the periodic shifts in the star's radial velocity measurements. An exoplanet is defined as an extra-solar planet orbiting a star that is not our sun. What makes it planetary as opposed to a star or a brown dwarf is defined by fusion thresholds and mass limitations. A star is characterized by its ability for sustained proton-proton fusion, with a hydrogen fusing limit at $0.075M_\odot$ separating the main sequence stars from brown dwarfs which are unable to perform this fusion. Brown dwarfs fall under this mass with a lower limit of $0.013M_\odot$, or roughly thirteen times the size of Jupiter. The lower constraint separates brown dwarfs from planetary objects by the deuterium fusion limit.

The first exoplanets found were large Jupiter sized bodies with short periods due to an observational bias (Charbonneau et al. 2007). Since then, advances in observational technology have made it possible to see the star-planet systems that were previously hidden from discovery. We are able to expand the lower mass constraints of exoplanets, limited only by the technology and methods that we are using. The first approach to exoplanet observations were the radial velocity method (Mayor & Queloz 1995), followed by the transit method (Henry et al. 2000). These remain the primary methods, while gravitational lensing and direct imaging are less prevalent techniques.

With the advent of cheap CCDs, large-scale transit surveys have become
much more practical. It is feasible for arrays of small telescopes, such as MEarth (Irwin et al. 2009), to stare at the same stars night after night, collecting enough light to detect transit signals with the use of sophisticated algorithms.

Two of the first ground-based exoplanet transit searches were the Optical Gravitational Lensing Experiment (OGLE) and the Trans Atlantic Exoplanet Survey (TrES) (Mandushev et al. 2005). Originally designed to look for dark matter, OGLE was repurposed to search for exoplanets through the transit and microlensing methods, with over a dozen detected to date (Udalski et al. 2004). TrES used an array of 3 telescopes in different locations to search for planets. Two of the most prolific searches from the ground are the HAT Network and the SuperWASP Consortium. HAT is a network of six small telescopes located across multiple sites around the globe to maintain full time coverage. It was the first to find a transiting system with multiple planets after a radial velocity follow-up on HAT-P-13 (Bakos et al. 2009). SuperWASP is a UK Consortium of eight academic institutions and has found over 20 exoplanets.

Not limited to ground-based observing, the exoplanet search expanded to space telescopes. Of these, Spitzer has made an enormous contribution in the infrared, capturing light from known hot Jupiter planets for the first time using planetary occultations (Deming et al. 2005). The Kepler Mission, launched in 2009, has also made dramatic progress in the field of exoplanets, observing a significant amount of very precise transits and occultations. In February 2012, they released 2321 planet candidates, an increase from the 1235 planet candidates that were released in February 2011 (Borucki et al. 2011).
1.1. The Transit Method

Looking for planetary eclipses has become one of the most useful practices for discovering and analyzing these exoplanets. Whether it is a transit, where the planet eclipses the star, or an occultation, where the star eclipses the planet, much information about the planetary system can be learned through an analysis of these light curves. An ideal light curve of a transiting planet is depicted in Fig. 1.

Observations of transits are useful tools for ascertaining properties of the exoplanet as well as its parent star. The relative area of the planet to the star can be determined by examining how much the star dims during a transit. There is a direct relationship between the depth of a transit light curve, \( \delta \), and the fractional area of the planet

\[
\delta = \left[ \frac{R_p}{R_*} \right]^2.
\]  

(1)

For example, a dimming of one percent implies that the exoplanet is one percent of the area of the star, or ten percent of the radius (Winn 2010). The precision of the actual value of \( R_p \) is relative to how well the stellar radius is known.

The parameters of the transit model that can be determined from a transit of an exoplanet are shown in Fig. 1. The impact parameter \( b \) where the planet crosses the star on an orbital plane is measured relative to the center of the star. The inclination angle \( i \) is measured relative to the center of the star from the line of sight to the orbital plane of the planet. Another important parameter is \( \frac{a}{R_*} \), the semi-major axis in units of radius of the parent star. These three parameters make up the geometry which determines the ability of a transit to
be observed with respect to our line of sight through the relationship

\[ b = \left[ \frac{a}{R_*} \right] \cos i. \]  

(2)

If \( b > 1 + \frac{R_p}{R_*} \) where \( R_p \) is the radius of the planet and \( R_* \) is the radius of the parent star, then the transit would not be visible. If \( b < 1 + \frac{R_p}{R_*} \) then the transit will be visible. However, if \( 1 + \frac{R_p(1-R_*)}{R_*} < b < 1 + \frac{R_p}{R_*} \) then the transit will be visible, but grazing.

Figure 1 The geometry of a transit. (Top) A side view of a transit depicting the impact parameter \( b \) and inclination \( i \). (Right) A front view of a transit showing the impact parameter \( b \), transit depth \( \delta \), and an ideal transit light curve reproduced from Winn (2010). This model does not include the effects of limb darkening.

The absolute mass of the planet to its star may be evaluated by combining these parameters in conjunction with radial velocity measurements. A small gravitational pull from the planet on its star causes a periodic red and blue shift in the spectral lines by changing the star’s velocity in our line-of-sight. This radial velocity change appears in the spectroscopic signal as a wobble about the star’s barycentre. These wobbles are proportional to the mass of the planet and its distance from its star, among other parameters, and are also a
function of the relative inclination of the planetary system to our line of sight. Knowing both the radial velocity of the star’s wobble relative to the Earth and the planetary inclination allows the planet’s mass to be calculated. Radial velocity measurements for our targets have been taken with other instruments, and can be combined with the inclination determined from transit photometry to provide the true planetary mass.

Transit light curves can provide more information than a planet’s relative area and mass. Abnormalities in transit light curves reveal other features of the star-planet system that may be unobservable. Flux anomalies and changes in transit depth are indications of potential star spots (Fig. 2), as discussed by Silva (2003). Variations in the timing of high precision transits could indicate the presence of additional planets or moons (Holman & Murray 2005).

![Fig. 2.- Abnormality in a transit light curve of GJ-1214b revealing suspected star spots. Reproduced from Carter et al. (2011).](image)

Obtaining data of both the transit and occultation further constrains the parameters of the exoplanetary orbit. The change in the time of conjunction, $\Delta t_c$, related to the orbital period $P$ and observer’s celestial longitude, $\omega$, 

provides a powerful limitation on the eccentricity, $e$, of the orbit.

\[ \Delta t_c \approx \frac{P}{2} \left[ 1 + \frac{4}{\pi} e \cos \omega \right] \]  

(3)

The range of eccentricity from observed exoplanets can shed light on planet formation and the evolution of orbits (Winn 2010).

Recently, the photometric precision of transit observations has become high enough that transmission spectroscopy of the upper atmosphere of an exoplanet can be measured. For a Jupiter-sized planet orbiting a Sun-sized star, there is a one percent transit depth. This means that the area of the planet plus its atmosphere contributes to a dimming of one percent of the area of the star. As gas giants or planets with atmospheres transit their stars, light is filtered through the upper atmosphere, causing the atmosphere to be slightly illuminated in comparison to the planet itself (Winn 2010). In order to measure transmission spectroscopy, an instrument must be accurate enough to measure a change proportional to the relative area of the atmosphere to the optically thick planetary body, which is of much less than one percent of the dimming of the star. Spectroscopic data provides details of the atmospheric composition based on the wavelength of light that passes through these atmospheres. For strong transits, commonly associated with hot Jupiter-like planets, the effective size of the planet will increase depending on the observation wavelength. This increase in size is classified by atmospheric scale heights

\[ H = \frac{k_b T}{\mu_m g}, \]  

(4)

where $k_b$ is Boltzmann's constant, $T$ is temperature, $\mu_m$ is the mean molecular mass, and $g$ is the local gravitational acceleration. This $H$ value relates the absorption of certain wavelengths to the mean molecular mass and temperature of
the planet, making it possible to determine an atmospheric composition (Winn 2010).

2. Observations

Observations were chosen based on transit prediction software made available by Poddany et al. (2010). Based on the date that each telescope was available, potential targets were listed and then one target was selected based on brightness of the parent star, transit depth, altitude, and transit duration among others.

Most transit observations were made using the MIT Optical Rapid Imaging System (MORIS), a PI instrument that is located on the three meter Infrared Telescope Facility (IRTF) on Mauna Kea, HI. It is a visible wavelength camera that has been mounted on the side window of the spectrograph SpeX, providing the opportunity for simultaneous observation at visible as well as infrared wavelengths. For more details see Gulbis et al. (2011).

The MORIS field of view is 60 arcsec x 60 arcsec, the same as for SpeX. MORIS uses an Andor iXon EM+ DU-897 camera with a 512x512 E2V CCD97 with low read noise, low dark current, and a quantum efficiency greater than 90 percent. The camera is cooled thermoelectrically to an average of -70°C for all observations. MORIS has 3:1 reducing optics and a 10-slot filter wheel. Observations were made using a variety of the available Sloan filters, specifically Sloan i' and Sloan r'. The Spectrum Instruments Intelligent Reference TM-4 GPS system was utilized for internal and external triggering of the camera with < 1μs accuracy. A range of exposure times was used during observations due to variations in weather and seeing conditions.
Additional observations were made using the Butler University Holcomb Telescope, as well as with SARA North and SARA South, two instruments available through the Southeastern Association for Research in Astronomy (SARA) Consortium, of which Butler University is a member.

The Holcomb telescope is a 38 inch Cassegrain reflecting telescope located on the Butler University campus in Indianapolis, Indiana. The Holcomb field of view is 5 arcmin x 7 arcmin. It uses an Apogee Alta E6 camera with a 1024x1024 Kodak KAF1001E with low read noise, low dark current, and a quantum efficiency around 70 percent. The camera is cooled to an average of -20°C for all observations. Observations were made using the Bessel R filters with a range of exposure times as variations in weather and seeing conditions occurred.

SARA South is a 0.6 meter telescope located at the Cerro Tololo Inter-American Observatory (CTIO) in Cerro Tololo, Chile. The SARA South field of view is 10 arcmin x 10 arcmin. It uses the Holcomb's Apogee Alta E6 camera. The camera is cooled to an average of -20°C for all observations. Observations were made using the Bessel R filter with a range of exposure times as variations in weather and seeing conditions occurred.

SARA North is a 0.9 meter telescope located at the Kitt Peak National Observatory (KPNO) in Kitt Peak, Arizona. The field of view is 13.6 arcmin x 13.6 arcmin. It uses an Apogee Alta U42 camera with low read noise, and a quantum efficiency greater than 90 percent. The camera is cooled to an average of -35°C for all observations. Observations were made using the Bessel R filter with a range of exposure times as variations in weather and seeing conditions occurred.
2.1. Selected Exoplanet Targets

This paper discusses six exoplanets GJ-1214b, TrES-1b, TrES-3b, WASP-16b, WASP-36b, and XO-2b. Special emphasis is given to the observations and analysis of TrES-1b.

TrES-1b, discovered by Alonso et al. (2004), is a hot, Jupiter sized planet with radius $R_p = 1.081 \pm 0.029 \, R_{Jup}$, that orbits a K0V star. The orbital period of TrES-1b is $P = 3.0300737 \pm 0.0000026$ days (Winn et al. 2007). Of particular interest are abnormalities in the observed transit flux of TrES-1. The possibility of star spots or another smaller planet with a larger orbit was suggested by Rabus et al. (2009). Subsequent observations proposed that star spots, rather than an additional transiting planet most likely caused the anomalies (Dittmann et al. 2009). A collection of observations made using the IRTF-MORIS, Holcomb Telescope, as well as archived data have been collected to analyze the system.

GJ-1214b was observed using the IRTF-MORIS. It is smaller than TrES-1b. With a radius of $R_p = 2.678 \pm 0.13 \, R_{Earth}$ and mass $M_p = 6.55 \pm 0.98 \, M_{Earth}$ (Charbonneau et al. 2009), GJ-1214b has been termed a "super-Earth". The orbit of this super-Earth is $P = 1.5803925 \pm 0.0000117$ days around an M dwarf. This system contains flux anomalies, which are most likely caused by small star spots as opposed to additional bodies. Berta et al. (2011) constrained the likely characteristics of an additional planet, limiting the possibilities to an object smaller and cooler than GJ-1214b. Thus, star spots seem to be the more probable explanation. Recently, Carter et al. (2011) has observed two of these star spot transit events.

XO-2b is another hot Jupiter with radius $R_p = 0.996 (^{+0.031}_{-0.018}) \, R_{Jup}$ and
mass $M_p = 0.565 \pm 0.054 \, M_{Jup}$ (Fernandez et al. 2009). The period observed for this planet is $P = 2.615857 \pm 0.000005$ days (Burke et al. 2007) around a KOV star. These transits were observed with the IRTF-MORIS and the Holcomb Telescope.

One transit observation made of each of the following systems has been included for analysis. The transit of TrES-3b was observed with the IRTF-MORIS. TrES-3b is a gas giant with radius $R_p = 1.302 \pm 0.057 \, R_{Jup}$ (Christiansen et al. 2011) and mass $M_p = 1.910 \, (^{+0.075}_{-0.060}) \, M_{Jup}$ (Sozzetti et al. 2009). It orbits around a G star with an observed period of $P = 1.30619 \pm 0.00001$ days (O’Donovan et al. 2007). SARA North was used to observe the transit of WASP-36b, another giant, orbiting a G2 star. It has a radius $R_p = 1.281 \pm 0.029 \, R_{Jup}$ and mass $M_p = 2.303 \pm 0.068 \, M_{Jup}$. The observed period is $P = 1.537365 \pm 0.000003$ days (Smith et al. 2012).

One southern hemisphere transit observation, made with SARA South, was found in archived data and its analysis has been added to this project. WASP-16b is a Jupiter sized planet with radius $R_p = 1.008 \, (^{+0.083}_{-0.066}) \, R_{Jup}$ (Lister et al. 2009) and mass $M_p = 0.855 \, (^{+0.043}_{-0.076}) \, M_{Jup}$. It orbits a G3V star with an observed period of $P = 3.11860 \pm 0.00001$ days (Lister et al. 2009).

A summary of the observation nights, telescope facility, filters used, exposure times, and number of images have been included in Table 1.
Table 1: Exoplanet Observations Summary

<table>
<thead>
<tr>
<th>Planet</th>
<th>Date of Observation</th>
<th>Telescope Facility</th>
<th>Filter</th>
<th>Range of Exposures (s)</th>
<th>No. of Frames</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>GJ-1214b</td>
<td>2011-05-29</td>
<td>IRTF-MORIS</td>
<td>Sloan i'</td>
<td>5-120</td>
<td>57</td>
<td>tracking problems</td>
</tr>
<tr>
<td></td>
<td>2011-06-09</td>
<td>IRTF-MORIS</td>
<td>Sloan i'</td>
<td>40-150</td>
<td>89</td>
<td>cloudy</td>
</tr>
<tr>
<td>TrES-1b</td>
<td>2007-10-07</td>
<td>Holcomb</td>
<td>Bessel R</td>
<td>60</td>
<td></td>
<td>tracking issues, cloudy</td>
</tr>
<tr>
<td></td>
<td>2009-06-25</td>
<td>IRTF-MORIS</td>
<td>Sloan r'</td>
<td>3-20</td>
<td>5087</td>
<td>bright flash</td>
</tr>
<tr>
<td></td>
<td>2009-06-28</td>
<td>IRTF-MORIS</td>
<td>Sloan r'</td>
<td>1-2</td>
<td>7811</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2009-07-01</td>
<td>IRTF-MORIS</td>
<td>Sloan r'</td>
<td>2</td>
<td>8150</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2009-07-10</td>
<td>IRTF-MORIS</td>
<td>Sloan r'</td>
<td>5-120</td>
<td>2751</td>
<td>cloudy</td>
</tr>
<tr>
<td>TrES-3b</td>
<td>2011-05-27</td>
<td>IRTF-MORIS</td>
<td>Sloan i'</td>
<td>30-60</td>
<td>262</td>
<td>high humidity</td>
</tr>
<tr>
<td>WASP-16b</td>
<td>2010-05-10</td>
<td>SARA South</td>
<td>Bessel R</td>
<td>20</td>
<td>412</td>
<td>-</td>
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<tr>
<td>WASP-36b</td>
<td>2012-01-29</td>
<td>SARA North</td>
<td>Bessel R</td>
<td>40</td>
<td>246</td>
<td>high atmospheric disturbance</td>
</tr>
<tr>
<td>XO-2b</td>
<td>2007-11-28</td>
<td>Holcomb</td>
<td>Bessel R</td>
<td>60</td>
<td>242</td>
<td>tracking issues</td>
</tr>
<tr>
<td></td>
<td>2011-02-04</td>
<td>IRTF-MORIS</td>
<td>Sloan i'</td>
<td>8-10</td>
<td>2867</td>
<td>-</td>
</tr>
</tbody>
</table>
3. Image Analysis and Transit Light Curves

The image analysis methods used for observations made with the IRTF-MORIS are similar to those described in Adams et al. (2010) for OGLE-TR-111b. During each observation, images are taken as a series of datacubes. Data was analyzed using image tools in IRAF\(^1\), with specific task names italicized. These images are separated with `imslice` along the image frames, and a series of separate image fits files are created. For the Holcomb and SARA observations, images were taken individually and these image splitting steps were not taken.

Bias images to correct for the noise generated by the CCD's electronics are taken for all observations in complete darkness with a zero exposure time, and then are median combined into a master bias with `imcombine`. This master bias is then subtracted from the individual flat images with `imarith`. Flats, images of an evenly illuminated background, are used to correct for the CCD pixel variations, caused by intrinsic variations and hot pixels. The bias-corrected flats are median combined and mode scaled. Using `imstat` the mean is found and then used to normalize the master flat. The data images are corrected by subtracting the master bias and then dividing by the normalized master flat to remove variation across the whole CCD.

Once the images have been reduced, a python script is used to create object folders and define the image files that will be used during the photometry. For the observations taken with MORIS, information about the file names, initialization time, and the exposure times are specified from the observing log.

\(^1\)IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
since MORIS does not contain this information within the fits header. For the Holcomb and SARA observations, initialization and exposure times are found within the fits header and collected with an additional script. Within this organizational process, image frame times are converted from Universal time into Julian dates.

Photometry is performed on the very first image frame using the `phot` package in IRAF. The target star and its companion stars are selected from the first image field. Each subsequent image is then centered based on the position of the previous frame to correct for drifting caused by problematic tracking, and random jumps in the data caused by removing bad frames or by telescope glitches.

Aperture photometry is used to remove the sky background and observe the variation in light caused by a transiting object. This is performed for a large range of aperture radii, since the best aperture is not necessarily known beforehand due to variations in the seeing among other factors. Choosing too small of an aperture limits the amount of area, restricting the amount of light considered, and the entire transit may be lost. Meanwhile, choosing too large of an aperture incorporates too much background noise. The aperture radii are measured from the center of the star with an initial range usually between two to fifty pixels (0.22 to 5.50 arcseconds). In order to correct for variations in the atmosphere during the observation period, differential photometry is performed relative to one or more comparison stars. The number of counts of the target star in each aperture is divided by the counts of the comparison star. This flux ratio is then normalized by dividing the flux by the mean flux out of transit and plotted as a function of time, creating nine light curves,
as shown in Fig. 3. If the comparison star differs in color from the star in the planet system, atmospheric extinction may occur causing the normalized lightcurves to appear sloped out of transit. This trend is corrected for within the fitting process.

An iterative approach is then taken to minimize the error on the out of transit flux. Sky regions, ranging from 5.5 to 16.5 arcseconds, can be altered to determine a sky background count which reduces the noise of the light curves. From the best sky region and large range of apertures, the light curve with the lowest scatter out of transit, is selected. Then the process is repeated for a smaller range of apertures surrounding the best light curve. Sometimes it is reasonable to redefine the out of transit region based on the refined photometry. This process is completed multiple times until the aperture with the best precision and flattest out of transit data is identified. A summary of these values are included in Table 2. These curves are then binned to resample the data and reduce the noise. Fig. 4 contains the binned light curves for the objects observed.
Fig. 3.— Broad range of apertures for TrES-3 from 1.1 to 5.5 arcseconds. From these plots, a smaller range can be identified to contain high precision values. Data taken on 05-27-2011 with IRTF-MORIS.
Table 2: Best Photometry Settings By Observation

<table>
<thead>
<tr>
<th>Planet</th>
<th>Date of Observation</th>
<th>Telescope</th>
<th>Size of Aperture (arcsec)</th>
<th>Sky Region (arcsec)</th>
<th>Scatter in Flat Data (normalized flux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GJ-1214b</td>
<td>2011-05-29</td>
<td>MORIS</td>
<td>1.65</td>
<td>7.70</td>
<td>0.0044</td>
</tr>
<tr>
<td></td>
<td>2011-06-09</td>
<td>MORIS</td>
<td>1.10</td>
<td>9.90</td>
<td>0.0039</td>
</tr>
<tr>
<td>TrES-1b</td>
<td>2007-10-07</td>
<td>Holcomb</td>
<td>1.54</td>
<td>9.90</td>
<td>0.0015</td>
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<tr>
<td></td>
<td>2009-06-25</td>
<td>MORIS</td>
<td>4.40</td>
<td>6.60</td>
<td>0.0039</td>
</tr>
<tr>
<td></td>
<td>2009-06-28</td>
<td>MORIS</td>
<td>5.50</td>
<td>6.60</td>
<td>0.0049</td>
</tr>
<tr>
<td></td>
<td>2009-07-01</td>
<td>MORIS</td>
<td>4.40</td>
<td>9.90</td>
<td>0.0090</td>
</tr>
<tr>
<td></td>
<td>2009-07-10</td>
<td>MORIS</td>
<td>2.20</td>
<td>4.40</td>
<td>0.0081</td>
</tr>
<tr>
<td>TrES-3b</td>
<td>2011-05-27</td>
<td>MORIS</td>
<td>4.95</td>
<td>11.00</td>
<td>0.0018</td>
</tr>
<tr>
<td>WASP-16b</td>
<td>2010-05-10</td>
<td>SARA South</td>
<td>1.32</td>
<td>6.60</td>
<td>0.0031</td>
</tr>
<tr>
<td>WASP-36b</td>
<td>2012-01-29</td>
<td>SARA North</td>
<td>1.10</td>
<td>8.80</td>
<td>0.0039</td>
</tr>
<tr>
<td>XO-2b</td>
<td>2007-11-28</td>
<td>Holcomb</td>
<td>1.65</td>
<td>11.00</td>
<td>0.0018</td>
</tr>
<tr>
<td></td>
<td>2011-02-04</td>
<td>MORIS</td>
<td>4.40</td>
<td>8.80</td>
<td>0.0015</td>
</tr>
</tbody>
</table>
Fig. 4.— Binned light curves for the best aperture photometry of each observation by planet. Note that some light curves contain slopes which are corrected for in the fitting stage.
WASP-16b
WASP-16b 20100510-SSARA 1.32 arcsec
Precision: +/-0.0031

WASP-36b
WASP-36b 20120129-SARA 1.1 arcsec
Precision: +/-0.00392

TrES-3b
TrES-3b 20110527-MORIS 4.95 arcsec
Precision: +/-0.0018
TrES-1b

TrES-1b 20071006-HOLCOMB 1.54 arcsec
Precision: +/-0.00145

TrES-1b

TrES-1b 20090625-MORIS
4.4 arcsec Precision: +/-0.00392

TrES-1b

TrES-1b 20090628-MORIS 5.5 arcsec
Precision: +/-0.00485
TrES-1b
TrES-1b 20090701-MORIS 4.4 arcsec
Precision: +/-0.00895

Image Frame vs. Normalized Flux

TrES-1b 20090710-MORIS 2.2 arcsec
Precision: +/-0.0081

Image Frame vs. Normalized Flux
As a further check to determine the accuracy of the data, several observational statistics are plotted as a function of time. This set of plots is shown in Fig. 5. The normalized flux ratio for the best aperture as well as its binned image are included as a reference for the other plots in the presence of variations and anomalies. In addition, the counts of the target star and its companion, the coordinates of the center of the target star, and the full-width-half-maximum (FWHM) of a Gaussian fit are incorporated. These
quantities are useful for inspecting strange features that appear in the light curves. Since abnormalities could imply sunspots or additional planets, it is necessary to cross-reference these variations, because a sudden pixel jump may have the same signature as a real variation.
Fig. 5.— Analysis of observation conditions for TrES-3b data taken on 05-27-2011 with IRTF-MORIS. Note the sudden decrease of photons in the target and comparison star counts as the exposure time was decreased to prevent saturation. In addition, the noise in ingress correlates to a spike in seeing.
4. Transit Light Curve Model Fitting

Once we have done the final photometry, we can fit the best light curve to determine the transit parameters. The model fitting methods we use are similar to that of Carter et al. (2011) which uses a Markov chain Monte Carlo (MCMC) algorithm. An MCMC algorithm is a procedure used for determining a collection of random draws from a posterior probability distribution (Holman et al. 2006). MCMC algorithms are good at fitting for highly correlated variables, such as $i$ and $\frac{R_p}{R_*}$. Within this method, slopes may be fixed or variable to correct for transit light curve trends. The causes for these trends vary, but may be attributed to increase in cloud cover, changes in seeing, and atmospheric extinction among others. The stellar limb-darkening coefficients are quadratic and fixed to values calculated with the Claret (2004) limb darkening values, using the jktld program by Southworth (2008) as seen in Table 3.

4.1. Markov Chain Monte Carlo Fitting

We begin the fitting method with the relationship

$$F = f(\bar{p}, t) + x,$$

where $x$ represents the error, which is assumed to take on a Gaussian distribution of width $\sigma$. This $\sigma$ value is the noise from the out of transit data. $F$ is the measured normalized flux from our observations, $f(\bar{p}, t)$ is the transit model described by the fit parameters, and $F - f(\bar{p}, t)$ are the residuals specific to each night, $x$.

In a multidimensional parameter space, an initial value is chosen from which to begin the MCMC chain. A likelihood $L_i = L(\bar{p})$ is associated with
this choice of parameters based on the relationship

\[ \mathcal{L} \propto \exp \left( -\frac{\chi^2}{2} \right), \]  

(6)

where the statistic \( \chi^2 \) is defined by

\[ \chi^2 = \sum \frac{(F - f(\vec{p}, t))}{\sigma^2}. \]  

(7)

A parameter offset, \( \vec{J} \), or "jump", is drawn from a jump size distribution. This new set of parameter values has a likelihood of \( \mathcal{L}(\vec{p} + \vec{J}) \). This new likelihood is compared to the initial likelihood and the jump is "accepted" or "rejected" using the Metropolis-Hastings Jump Acceptance Criterion (Tegmark et al. 2004):

1. If \( \mathcal{L}(\vec{p}_i + \vec{J}) > \mathcal{L}(\vec{p}_i) \) then accept the jump and \( \vec{p}_{i+1} = \vec{p}_i + \vec{J} \).
2. If $\mathcal{L}(\tilde{p}_i + \tilde{j}) < \mathcal{L}(\tilde{p}_i)$ then accept the jump with a probability of $\left[ \frac{\mathcal{L}(\tilde{p}_i + \tilde{j})}{\mathcal{L}(\tilde{p}_i)} \right]$. Otherwise, reject the jump and $p_{i+1} = \tilde{p}_i$.

We ran our chains with 100,000 links, so that each parameter had converged on a common value and the parameter space about that value was well sampled, shown in Fig. 6.
Fig. 6.— Convergence to parameter fitting for TrES-3b light curve. Data taken on 05-27-2011 with IRTF-MORIS.
4.2. Comparison to Other Observations

The light curve fits were compared to previous observations in order to determine their accuracy, as well as to analyze the accuracy of the reference ephemerides. To do this, a reference period and reference mid-transit time were set from previously published data. The epoch and observed minus calculated mid-transit time \((O - C)\) for individual observations by other groups were downloaded from the Exoplanet Transit Database. This database contains a compilation of transit observations completed by professional and amateur astronomers. The data quality of these observations are ranked from one to five based on light curve precision. Within our comparison, a filter was applied and only transits with data quality of two or higher and with mid-transit time errors less than two minutes have been included. These values can be used for comparison purposes, but can not be fully relied upon as observations may include errors due to imperfect timing or incorrect conversion to Barycentric Julian Dates, among others. Database data are labeled by teal • dots for professional observations, and by blue x for amateur data.

The \(O - C\) values for our data were determined using the reference period and mid-transit time. Our mid-transit times are calculated in \(J_{DUTC}\), but for comparison with additional data, they are converted into Barycentric Julian Days (BJD) using the program created by Eastman et al. (2010). These BJD values are our observed mid-transit times. To find the calculated values, the epoch is determined by subtracting the reference mid-transit time from our value, dividing by the reference period, and rounding the resulting value to the nearest integer value. With the integer value, getting the calculated mid-transit time is as easy as adding the epoch times the reference period to the
reference mid-transit time.

Our $O - C$ values are combined with the values of the other observations and are then plotted versus the epoch. With a correct ephemeris value, we should expect to see a trend line with a slope of zero which would suggest the timing is consistent. The filter applied to remove low quality observations reduces some of the deviation from this trend line. Another possible source of deviation is incorrect conversion to BJD, which could cause a ±1 minute offset that would not be removed by our filters. The $O - C$ results for each target can be found at the conclusion of the respective fitting analysis sections.

4.3. Fitting the GJ-1214b Light Curves

The GJ-1214b light curves were the most difficult to fit. Due to cloudy conditions which caused bad seeing and low counts, the observational data for the transit of GJ-1214b were poor. This led to unreliable photometry. For the second half of the night of 2011-05-29, frames 46 to 57 were not included in the fitting process. The cloud cover at that point was so dense that the stars were hardly visible, and the photon counts were decreasing at a rate that produced a false egress in the data. Cloud cover was also a problem for the night of 2011-06-09. It caused high noise in and out of transit, making even the best light curve difficult to fit. Individual fits are suspect due to the unreliable photometry for this data set.

Due to the low precision of our light curves, the parameters differ significantly from previous values. The radius ratio we found had a value of $\frac{R_p}{R_e} = 0.0993 \pm 0.0069$, which was different from the value provided by Charbonneau et al. (2009), $0.1162 \pm 0.0007$, by $2.4\sigma$. Our inclination of $90.0 \pm 1.9$
degrees differed from the Berta et al. (2011) value, $88.80^{+0.25}_{-0.20}$, by 0.63σ. Our $\frac{a}{R_*}$ had a value of $14.9 \pm 2.1$, which differed from the value published by Berta et al. (2011) of $14.93 \pm 0.24$ by less than one σ. The transit midtimes, as one of the more robustly-determined parameters, are compared to previous work. All of the parameter values determined for the individual and joint fits are located in Table 10. The light curve fits and their residuals can be found in Fig. 7.

Fig. 7.— Light curve fits for GJ-1214b data taken on (left) 2011-05-29 and (right) 2011-06-09. The black crosses show individual data. The lines are the joint model fit. The lower panel shows the residuals (data minus model).
4.3.1. Comparison to Other Observations

Due to the unreliability of the two MORIS GJ-1214b data sets, the (O-C) values determined by the mid-transit time fits do not appear consistent with the reference ephemeris and Exoplanet Transit Database values (Table 4). Figure 8 demonstrates a horizontal trend when the MORIS data is neglected, indicating that the current ephemeris is probably correct.

![Graph showing mid-transit times for GJ-1214b](image)

Fig. 8.— (O-C) Mid-Transit times for GJ-1214b.

Table 4: GJ-1214b Time Results

<table>
<thead>
<tr>
<th>Date</th>
<th>Epoch #</th>
<th>O-C (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011-05-29</td>
<td>462</td>
<td>-425</td>
</tr>
<tr>
<td>2011-06-09</td>
<td>469</td>
<td>-307</td>
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</table>
4.4. Fitting the TrES-3b Light Curve

The conditions during the observations of the TrES-3b transit were excellent, and the comparison star chosen during the photometry was of comparable magnitude and size, causing the generated light curve to contain little noise. As a result, the MCMC algorithm easily fit the data. The residuals were low and the parameters found are consistent with previously determined values.

The radius ratio we found had a value of $\frac{R_p}{R_*} = 0.1651 \pm 0.0016$, which is consistent with the value provided by Sozzetti et al. (2009), $0.1655 \pm 0.0020$, to $0.2\sigma$. Our inclination of $82.08 \pm 0.13$ degrees is also consistent with the Sozzetti et al. (2009) value, $81.85 \pm 0.16$, to $1.1\sigma$. Our $\frac{a}{R_*}$ had a value of $6.080 \pm 0.058$, which is slightly less consistent with the value published by Sozzetti et al. (2009) of $5.926 \pm 0.056$ to $1.9\sigma$. The parameter values determined by the individual fit are located in Table 11. The light curve fit and its residuals can be found in Fig. 9.

Fig. 9.— Light curve fit for TrES-3b data taken on 2011-05-27. The black crosses show individual data. The lines are the individual model fit. The lower panel shows the residuals (data minus model).
4.4.1. Comparison to Other Observations

The (O-C) value from the TrES-3b observation in addition to the database values appear consistent with the reference ephemeris (Table 5), as demonstrated by the horizontal trend seen in Fig. 10, indicating that the current ephemeris is correct.

![Graph showing TrES-3b data](image)

Fig. 10.— (O-C) Mid-Transit times for TrES-3b.

Table 5: TrES-3b Time Results

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<tbody>
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<td>2011-05-27</td>
<td>896</td>
<td>65</td>
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</table>
4.5. Fitting the WASP-16b Light Curve

The analysis of the WASP-16b data suggests that the conditions during the observation were ideal, but the lack of a similar comparison star led to some noise in the analysis. Not many exoplanet observations have migrated to the southern hemisphere. As a result, there are few published analyses of these systems. The WASP-16 system in particular currently has only one set of published lightcurves for parameter comparison by Lister et al. (2009). Overall, the parameter values resulting from our fits are consistent with these values.

Our radius ratio had a value of $\frac{R_p}{R_*} = 0.1113 \pm 0.0046$, which is consistent with the value provided by Lister et al. (2009), $0.1095 \pm 0.0024$ to 0.35σ. The inclination we found, $84.74 \pm 0.74$ degrees, is consistent to 0.56σ with the Lister et al. (2009) value, $85.22 \pm 0.37$. For $\frac{a}{R_*}$, the value we found, $8.99 \pm 0.89$ was consistent with the Lister et al. (2009) value, $9.57 \pm 0.99$, to 0.44σ. The parameter values determined by the individual fit are located in Table 12. The light curve fit and its residuals can be found in Fig. 11.
4.5.1. Comparison to Other Observations

Due to the limited observations of WASP-16b, few transits from the database met our quality filter. Of these transits, only one was previously published (Lister et al. 2009) and it was from this publication that we found our reference ephemeris. The lack of quality data raises difficulties in distinguishing whether there is a trend present. As a result our O-C value (Table 6) and subsequent plot was inconclusive in determining the validity of the current reference ephemeris (Fig. 12).
Fig. 12.— (O-C) Mid-Transit times for WASP-16b.

Table 6: WASP-16b Time Results

<table>
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<td>2010-05-10</td>
<td>238</td>
<td>-236</td>
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</table>
4.6. Fitting the WASP-36b Light Curve

During the beginning of the observation of WASP-36b, the target was fairly low in the sky and the seeing was not ideal, so the photon count was low. This caused the beginning of transit to have some noise, which interfered with the fit causing some inconsistency with the fit parameters compared to published values.

Our radius ratio had a value of $\frac{R_p}{R_\star} = 0.1269 \pm 0.0040$, which is inconsistent with the value provided by Smith et al. (2012), $0.10485 \pm 0.00072$ to 2.8σ. The inclination we found, $88.8 \pm 4.1$ degrees, is consistent with the Smith et al. (2012) value, $83.61 \pm 0.21$, to 1.3σ. For $\frac{a}{R_\star}$, the value we found, $6.80 \pm 0.67$ was consistent with the previous value found by Smith et al. (2012), $5.977 \pm 0.082$, to 1.2σ. The parameter values determined by the individual fit are located in Table 13. The light curve fit and its residuals can be found in Fig. 13.

Fig. 13.— Light curve fit for WASP-36b data. The black crosses show individual data. The lines are the individual model fit. The lower panel shows the residuals (data minus model).
4.6.1. Comparison to Other Observations

Due to the limited observations of WASP-36b, only two transits from the database met our quality filter. Of these transits, only one was previously published (Smith et al. 2012) and it was from this publication that we found our reference ephemeris. The lack of quality data raises difficulties in distinguishing whether there is a trend present. As a result our O-C value (Table 7) and subsequent plot was inconclusive in determining the validity of the current reference ephemeris (Fig. 14).

![Graph showing O-C values for WASP-36b transits](image)

**Fig. 14.** (O-C) Mid-Transit times for WASP-36b.

### Table 7: WASP-36b Time Results

<table>
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<th>Date</th>
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</tr>
</thead>
<tbody>
<tr>
<td>2012-01-29</td>
<td>251</td>
<td>-515</td>
</tr>
</tbody>
</table>
4.7. Fitting the XO-2b Light Curve

XO-2 was the brightest target star of the four selected. A combination of a bright comparison star and stable weather conditions during the observation night of 2011-06-09 produced precise data. The fit was very smooth and when combined with the observation on 2007-11-28, the joint fit parameters were found to be mostly consistent with previously published values.

Our radius ratio had a value of $\frac{R_p}{R_*} = 0.10234 \pm 0.00043$, which is inconsistent with the value provided by Fernandez et al. (2009), $0.10485^{+0.00070}_{-0.00062}$ by 3σ. The inclination we found, $90.1 \pm 1.3$ degrees, is consistent with the Burke et al. (2007) value, $88.9 \pm 0.7$, by 0.8σ. For $\frac{a}{R_*}$, the value we found, $8.18 \pm 0.12$ was consistent with the previous value found by Fernandez et al. (2009), $8.13^{+0.09}_{-0.02}$, to 0.3σ. The parameter values determined by the individual fit are located in Table 14. The light curve fit and its residuals can be found in Fig. 15.
Fig. 15.— Light curve fits for XO-2b. The black crosses show individual data. The lines are the individual model fit. The lower panel shows the residuals (data minus model).
4.7.1. Comparison to Other Observations

Despite the quality of the observations, the time parameter fit for the 2011-06-09 observation does not appear consistent with the reference period (Table 8). This may be due to an incorrect ephemeris, but most likely is the result of a systematic error on our part, since the 2007-11-28 data, as well as the other database values, appear consistent (Fig. 16).

![Graph](image)

Fig. 16.— (O-C) Mid-Transit times for XO-2b.

Table 8: XO-2b Time Results

<table>
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<th>Date</th>
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<th>Epoch #</th>
<th>O-C (sec)</th>
</tr>
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<tbody>
<tr>
<td>2007-11-28</td>
<td>Holcomb</td>
<td>-13</td>
<td>-15</td>
</tr>
<tr>
<td>2011-02-04</td>
<td>MORIS</td>
<td>432</td>
<td>-387</td>
</tr>
</tbody>
</table>
4.8. Fitting the TrES-1b Light Curves

The transit of TrES-1b observed on 2009-06-25 contained very low levels of noise and mostly good quality frames. A few frames were removed due to a bright flash resulting from an unknown source as well as a jump caused by a tracking error. These occurred very close to mid-transit. When the photometry was completed the flux was mismatched around this point, causing the light curve halves to not match up. So, these two halves were renormalized separately for the fitting process. The transits observed on 2009-06-28 and 2009-07-01 produced smoother light curves, so no additional normalization was necessary. On 2007-10-07 there were a few tracking problems and clouds towards the end of the observation, so the parameter fit was not as consistent. Clouds were an issue for the observation of TrES-1b on 2009-07-10, and half of the light curve was lost due to low photon counts.

Despite the slightly worse photometry of 2009-07-10, the initial results of the joint fit for TrES-1b had low error. Our radius ratio had a value of \( \frac{R_p}{R_*} = 0.1315 \pm 0.0003 \) in the Sloan r' filter. This ratio differs by 6\( \sigma \) when compared to the value found by Winn et al. (2007) of 0.13686 \pm 0.00082 using the z' filter. This inconsistency is further analyzed in section 4.9.1.

The other parameters were consistent with the Winn et al. (2007) values. Our inclination was 90.000 \( \pm \) 0.097, compared to \( >88.4 \). The \( \frac{a}{R_*} \) value we found, 10.5260 \( \pm \) 0.0063, was consistent with the value provided by Winn et al. (2007), 10.45 \( \pm \) 0.15, to 0.5\( \sigma \).
4.8.1. Further Analysis of TrES-1b Transit Depth Variation

The inconsistency of the radius ratio values led to further analysis of the TrES-1b target. In order to account for potential analysis error, the Winn et al. (2007) values were refit using our fitting method. The parameter values resulting from the fit were consistent to less than 0.1σ with the published Winn et al. (2007) values. In addition, eleven transits of TrES-1b from Rabus et al. (2009) were incorporated into the fitting process in order to reduce error; eight with the Instituto de Astrofisica de Canarias (IAC) 80-cm telescope and three with the Hubble Space Telescope (HST).

The results of the 16 joint fit for TrES-1b helped reduce the radius ratio deviation. Our radius ratio had a value of \( \frac{R_p}{R_*} = 0.13501 \pm 0.00011 \) in the Sloan r' filter. This ratio now differs by 3σ when compared to the value found by Winn et al. (2007) of 0.13686 ± 0.00082 using the z' filter. The original inconsistency may be due to the MORIS half transit on 2009-07-10, and the additional data helped reduce the impact of this half curve. However, the value still remains inconsistent after a 16 joint fit, potentially indicating another explanation such as an instrumental effect, or even a difference in the depth vs. wavelength.

One interpretation of this inconsistancy is that the depth is smaller in r' than in z', suggesting the planet atmosphere is more opaque in z'. While the 16 observations were made in a red filter, the filters themselves differed by telescope and may add further depth variation. In response, each observation was fit individually and analyzed by the wavelength of the respective observation. The Winn et al. (2007) observations were made using the SDSS (Sloan) z' filter on the Fred Lawrence Whipple Observatory telescope with central wave-
length 925nm. The MORIS observations were made using the Sloan r' filter with central wavelength 622nm while the Holcomb data was taken in Bessel R with wavelength 660nm. The IAC observations used the Cousins R with central wavelength 647nm, and the Hubble Space Telescope data was taken using the G800L which spans 540nm to 1065nm. The depth by wavelength and by mid-transit time analyses appear in Fig. 17. The results of the depth analysis remain inconclusive and further investigation into the plausible causes of the radius ratio inconsistency is necessary.

Individual and joint fit parameter values are located in Table 15. The light curve fits and their residuals can be found in Fig. 18.
Fig. 17.— Transit Depth Variation for TrES-1b. (above) The radius ratio vs. filter wavelength depicts the depth changes in comparison to the filters used and their wavelength range. (below) The radius ratio vs. time shows depth variation over time, but does not show any particular trend.
Fig. 18.— Light curve fits for TrES-1b. The black crosses show individual data. The lines are the joint model fit. The lower panel shows the residuals (data minus model).

Holcomb

IRTF-MORIS
HST

HST

HST
4.8.2. Comparison to Other Observations

The Holcomb transit observation on 2007-10-06 was not included in Fig. 19 as its observed mid-transit time deviated over twelve minutes from the calculated value (Table 9). This may be due to a variety of factors, which may include but is not limited to the technical and environmental issues encountered during the observation, and a systematic error. The additional lightcurves from Rabus et al. (2009) are included in our O-C plot to improve the quality of the ephemeris analysis. Excluding the radius ratio, the fit parameters were consistent with previously published values, so we should expect the mid-transit times to also be consistent. However, the (O-C) mid-transit times that we plotted, in addition to the times from the database, depict a slight trend. This may indicate that the reference ephemeris is incorrect. Further observations of TrES-1b could confirm this trend and should be pursued.

![Fig. 19.— (O-C) Mid-Transit times for TrES-1b.](image)
Table 9: TrES-1b Time Results

<table>
<thead>
<tr>
<th>Date</th>
<th>Telescope</th>
<th>Epoch #</th>
<th>O-C (sec)</th>
</tr>
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Table 10: GJ-1214b Best Fit Parameters and Errors

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<th>Inclination</th>
<th>AperRstar</th>
<th>OOT Flux</th>
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<th>Mid-Transit Time</th>
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<td>2011-05-29</td>
<td>MORIS</td>
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<td>1.562 ± 0.026</td>
<td>9.66 ± 0.63</td>
<td>1.01876 ± 0.00084</td>
<td>0.36 ± 0.01</td>
<td>2455710.9052 ± 0.0022</td>
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<tr>
<td>2011-06-09</td>
<td>MORIS</td>
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<td>16.45 ± 0.29</td>
<td>1.00145 ± 0.00016</td>
<td>0.0137 ± 0.0018</td>
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<tr>
<td><strong>Joint Fit</strong></td>
<td><strong>MORIS</strong></td>
<td><strong>0.0993 ± 0.0069</strong></td>
<td><strong>1.572 ± 0.033</strong></td>
<td><strong>14.9 ± 2.1</strong></td>
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<td>2011-05-29</td>
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<td>1.0031 ± 0.0014</td>
<td>0.063 ± 0.040</td>
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Table 11: TrES-3b Best Fit Parameters and Errors

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<th>Mid-Transit Time</th>
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<tbody>
<tr>
<td>2011-05-27</td>
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Table 12: WASP-16b Best Fit Parameters and Errors

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Table 13: WASP-36b Best Fit Parameters and Errors

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Table 14: XO-2b Best Fit Parameters and Errors

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Table 15: TrES-1b Best Fit Parameters and Errors

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Additional Fits

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Joint Fit

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5. Discussion

Observations were performed with the IRTF-MORIS instrument for the exoplanets GJ-1214b, TrES-1b, TrES-3b, and XO-2b. Using the northern SARA telescope, observations were made of the exoplanet WASP-36b. Exoplanet transits of the targets TrES-1b and XO-2b, observed with Butler University's Holcomb Telescope, and of WASP-16b, observed with the southern SARA telescope, were added from archived files. This data was reduced and photometry was performed to find the flux variation due to the planetary transit. Light curves were created and a fitting algorithm was used to determine the system parameters: radius ratio, inclination, orbital distance \( \frac{a}{R_*} \), and mid-transit time. The mid-transit times were then compared to other observational results using O-C plots.

Unfortunately, the poor quality of the GJ-1214b light curves, due to both poor weather and a lack of bright comparison stars in the field of view, render the data only marginally useful for scientific analysis. This data demonstrated the difficulty of ground-based observations, which are subject to inconvenient weather and variation in seeing. It also demonstrated the importance of using a comparison star with close to the same brightness so that accurate differential photometry can be performed. Further transit observations would be necessary to decrease the error associated with these fits, and determine a much better light curve. Carter et al. (2011) found that an analysis of the transit depth could provide evidence of star spots, making additional observations in a variety of wavelengths a useful future goal.

The TrES-1b observations consisted of five nights which produced much better quality data than the GJ-1214b observations. The lack of transit depth
variations within the four MORIS transits, which were taken within a month of each other, suggests that TrES-1 is not a very spotty star, or that the pattern of star spots changes slowly. In addition, our TrES-1b radius ratio in the Sloan r' filter differed from previous values taken in z' by 3 σ, which may suggest that the atmosphere of TrES-1b is more opaque in the z' band. Another interesting feature about TrES-1b was the slope of the O-C plot. This could be due to unreliable amateur observations, or it could point to an incorrect ephemeris. Further observations of TrES-1b to investigate this timing would be crucial in interpreting the source of this trend.

The TrES-3b transit was easy to analyze and perfect for troubleshooting issues within the analysis. TrES-3 had analogous comparison star and clear nights. The resulting fits and low residuals were consistent with previous observations.

Analysis of XO-2b was made relatively easy due to the bright comparison star and stable weather conditions during the course of the observations. Some variation in fit parameters occurred, but observing additional transits may reduce this error. The timing analysis appeared to be mostly consistent with other observations on the Exoplanet Transit database.

WASP-16b was an observation found in archived files. It was made using the southern hemisphere SARA telescope, a region that has not been the focus of many exoplanet observers. The field surrounding WASP-16 does not yield analogous comparison stars, which made the analysis difficult. However, the parameter fits were consistent with previously published values. The mid-transit timing and reference ephemeris analysis remained inconclusive due to the scarcity of transit observations of this target.
The transit observation of WASP-36b started out less than ideal. This caused noise in ingress, which led to inconsistent radius ratio, and other slightly more consistent fit parameters. Like WASP-16b, WASP-36b is not a well observed target and a timing analysis could not be performed due to the lack of observations with sufficient data quality.

A special thanks to my research advisors, Dr. Brian Murphy, Dr. Elisabeth Adams, and Dr. Joshua Carter for their guidance throughout this project. I would also like to thank Dr. Christine Jones, Dr. Marie Machacek, and Dr. Jonathan McDowell for their dedication to the SAO REU Internship Program. This work is supported in part by the National Science Foundation Research Experiences for Undergraduates (REU) and Department of Defense Awards to Stimulate and Support Undergraduate Research Experiences (ASSURE) programs under Grant no. 0754568 and the Smithsonian Institution. Further support was given by Butler University and the Southeastern Association for Research in Astronomy (SARA). This research has made use of SAOImage DS9, developed by Smithsonian Astrophysical Observatory.
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