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Light Curve Analysis for Transiting Exoplanets

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Abstract

Exoplanetology is the study of planetary bodies orbiting around stars other than our own Sun. Since the launch of the Kepler Space Telescope on March 7, 2009 hundreds of these exoplanets have been discovered as they transit (pass in front of) their stars. Most have proven to be hot Jupiters: massive bodies that take only days to complete their orbits and are close to their stars. The intent of this research was to gather information on selected transiting exoplanets and compare the transit depths of different exoplanet types and transit geometries. Using an online database, exoplanets were selected by their sky location (declination higher than 30 degrees), magnitude (less than 12.5), and transit depth (greater than 0.0123). The equipment's ability to detect small magnitude changes is limited by sources of noise; if the transit depth were at or below the level of the noise, it would be difficult to even confirm, much less characterize, the event. The observational work was carried out two different times, once between September and December, 2011 and again between September and December, 2012. The work was performed at the Westside Observatory of Western Connecticut State University, using an f/8.1 20-inch Ritchey-Chrétien telescope equipped with a SBIG ST-7e charge-coupled device (CCD) camera and a Kron-Cousins R filter. After data collection, light curve analysis was performed on the exoplanets chosen. Some transits were observed multiple times for further analysis on the particular planet itself. The evaluation of noise sources in the observing system, and results for the stars CoRot-8, WASP-3, HAT-P-32 and WASP-33b will be reported.

Keywords: Exoplanet, Transit, Classification

1. Introduction

The Kepler Space Telescope has discovered hundreds of exoplanets since it was launched, and it continues to find more. The exoplanets vary in size and distance from their host star. For example, WASP-1b is 0.85 times the mass of Jupiter, has radius 1.42 times that of Jupiter and is 0.0387 AU from WASP-1 whereas WASP-8b is 2.18 times the mass of Jupiter, has a radius 1.08 times Jupiter's and resides 0.0792 AU away from WASP-8[1]. Earth observatories can detect an exoplanet by calculating the change in the magnitude of the host star when the planet transits (passes in front of) it. This change in magnitude is known as the transit depth and can be anywhere between ~ 0.0002 to ~ 0.0394 magnitude[2]. The differences are a result of the size of the planet and its distance from its star. A majority of exoplanets detected are hot Jupiters: massive bodies close to their stars. Typically, the hot Jupiters are ~0.05 AU from the host stars, have orbital periods between one and six days, and masses similar to Jupiter's[3]. Smaller Earth-sized planets will not affect the magnitude of the star as drastically as a hot Jupiter will.

Several other campaigns were initiated in search of exoplanets. The surveys include the Wide Angle Search for Planets (WASP) [4], the Hungarian Automated Telescope in search of extrasolar planets (HAT-P) [5], and the Convection Rotation and Planetary Transits (CoRot) [6]. All of the exoplanets currently discovered are listed on an online database, the Exoplanet Transit Database (ETD) [7], for public viewing. Other online databases are also available for public viewing such as Exoplanets Data Explorer[8]. Exoplanetary information such as right ascession, declination, transit depth, transit duration, visual magnitude of the star, and orbital period is listed. The website allows an observatory to input its longitude and latitude, and calculates an ephemeris for future transits observable from that location.

2. Methodology

Candidates for research were selected using the ETD. Candidates were selected by their declination (higher than 30 degrees), magnitude (less than 12.5), and transit depth (greater than 0.0123 mag). High declination is important because exoplanets can be tracked longer throughout the night at lower air mass and “seeing” is generally better. With this information, the exoplanets HAT-P-32, WASP-33, CoRot-8, and WASP-3 were selected for viewing; their properties are listed in Table 1.

Table 1. Exoplanet information

Planet Name	Right Ascension (J2000 epoch)	Declination (J2000 epoch)	Visual Magnitude	Transit Depth (mag)	Transit Duration (mins)	Period (days)
WASP-3b	$18^{h}34^{m}31.67^{s}$	$+35^{o}39^{'}41.9^{''}$	10.64	0.0123	137.0	1.846835
CoRot-8b	$19^{h}\ 26^{m}\ 21.245^{s}$	$+01^{o}25^{'}35.55^{''}$	14.8	0.0071	164.4	6.21272
HAT-P-32b	$02^{h}\ 04^{m}\ 10.24^{s}$	$+46^{o}41^{'}16.8^{''}$	11.29	0.0215	186.5	2.150008
WASP-33b	$02^{h}\ 26^{m}\ 51.08^{s}$	$+37^{o}33\ ^{'}02.5^{''}$	8.3	0.0151	163.0	1.2198669

The observations were conducted at Western Connecticut State University’s Westside Observatory. This observatory is equipped with an f/8.1 20-inch Ritchey-Chrétien telescope with a SBIG ST-7e charge-coupled device (CCD) camera and Kron-Cousins filters. The camera provided a 4 by 6 arc minute field of view. The images were grabbed using MaxIm DL version 2. The camera was initialized and imaging begun by choosing one of the five filters (UBVRI) with which the camera is equipped.

A number of dark, bias, and flat-field frames were taken to help calibrate and subtract the noise from the images when they were being processed. All of the dark, bias, and flat-field frames were combined to create median copies. Since the CCD chip creates thermal noise, the median dark frame was subtracted from each image to reduce this noise. The median bias frame was subtracted to reduce noise generated from the camera’s chip amplifier. The median flat-field frames were used to compensate for uneven sensitivity to light across the chip.

Each star was initially observed in four filters (B, V, R or I), to see which filter produced the highest signal to noise ratio. The reason for wanting a high ratio is to more clearly separate the stellar signal (high information content) from the sources of noise (low information content) in the system. In the case of both CoRot-8 and WASP-3, the R filter was chosen as best matching the peak wavelength sensitivity of the chip. Flat-field frames were also taken in the R filter. The exposure time for the image was chosen in MaxIm DL version 2. Long exposures for these dim stars were taken to ensure that more light could be captured by the chip to produce images with higher signal to noise. However, if exposure times were too long, the accuracy of transit time determinations would drop, and the images might trail due to telescope tracking errors. A balance had to be struck between these considerations.

Both HAT-P-32 and WASP-33 were also observed over multiple nights to obtain information on other planets that might reside in the system. Variations in transit times are estimated by tracking an exoplanet over many nights and comparing its light curves to identify any shifts in the start or end time of the transit. Also, if the transit has an increasing or decreasing transit depth, it could be a sign of orbital changes. In order to classify these planets as possible suspects for transit timing variation, the observed minus computed transit time (O-C) graph and the transit depth graph were both inspected. If there were any signs of an increasing or decreasing in the O-C or transit depth graphs, these planets became possible targets for study.

CoRot-8b was chosen because the creators of ETD had begun a campaign for observatories and amateurs to gather more information on this exoplanet. Though there were few transit observations, the O-C diagram as well as the transit duration vs. Epoch diagram showed small decreases. The transit depth vs. Epoch diagram illustrates a large increase, but with only two records. Noise is a limiting factor when dealing with very small transit depths (less than 0.0123 magnitude); it would be difficult to confirm a transit if it were at or below the level of noise. The transit depth of CoRot-8b is very small, and the star is very dim, but the Westside Observatory equipment was still able to image it. Before the imaging of CoRot-8b the transit depth was thought to be too small to be detectable (0.0071 mag), but to ensure the suspicions were correct it was observed regardless. Data collection on CoRot-8b occurred on only one night due to inclement weather, which produced a noisy light curve. The data was unusable because the transit was at the level of noise. The data points were uniformly scattered over the course of transit.

3. Results

Version 4 of MaxIm DL has a ring/aperture photometry option that was used to obtain magnitudes for the program stars and some non-varying comparison stars in the same fields. After analyzing the data for each star, light curves were produced. The light curves of WASP-33b and HAT-P-32b are excellent models for comparing the detectability of transits. The light curves for CoRot-8b and WASP-3b experienced large amounts of noise making it difficult to confirm that transits had even occurred during the observed nights. This was to be expected for CoRot-8b since the transit depth was 0.0071 mag. WASP-3b also has a transit depth which may be too small for the Westside Observatory equipment to detect. Due to the increasing clouds over the course of the night the data was skewed. WASP-3 was compared with two different stars in the field. The check star drifted close to the edge during the night so when it was analyzed part of the aperture went off of the screen. The comparison star did not drift toward the edge of the field, but the magnitude values recorded were inconsistent (large variations in the magnitude from one frame to the next). This may have been the result of the comparison star being dimmer then the drifting check star and the variable star.

3.1 Light Curve Data For HAT-P-32b

The light curves for HAT-P-32b are shown in Figure 1.

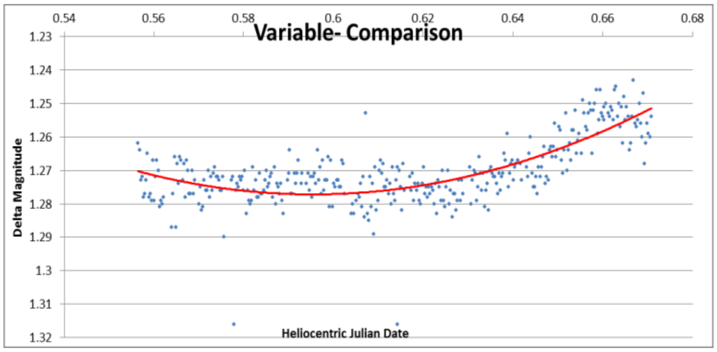

Figure 1a. HAT-P-32b Light Curve from November 19, 2011

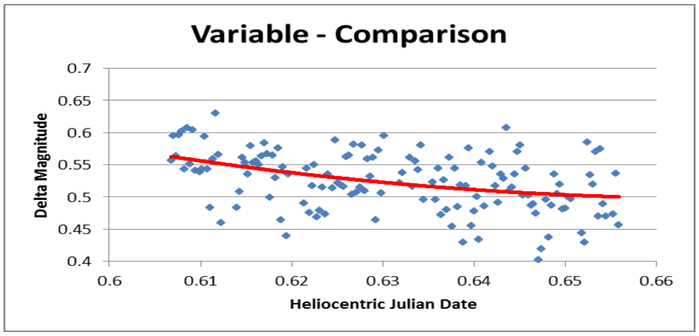

Figure 1b. HAT-P-32b Light Curve from November 26, 2012

Figure 1a exhibits a transit of HAT-P-32b. During the night of November 19, 2011 eighty-eight percent of the transit was captured and recorded. The graph shows that the transit depth closely matches that in the Exoplanet Transit Database (0.0215 mag), with an observational scatter of around ± 0.008 mag. During the night of November 26, 2012 around forty percent of the transit was captured. Since this data set is brief, no real conclusions can be made regarding changes in the transit depths or timings, but the information will be useful in comparison with future observations of this exoplanet.

3.2 Light Curve Data For WASP-33b

The light curves from WASP-33b can be seen in Figure 2.

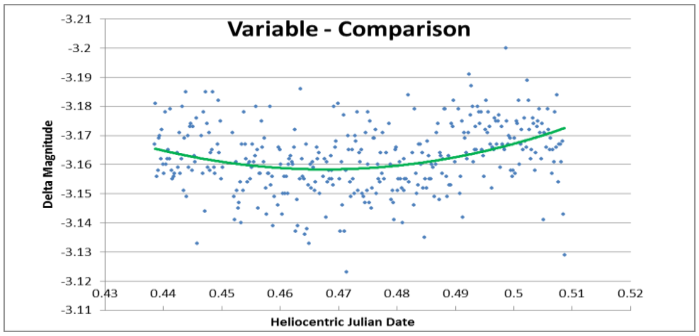

Figure 2a. WASP-33b transit data from November 7, 2011

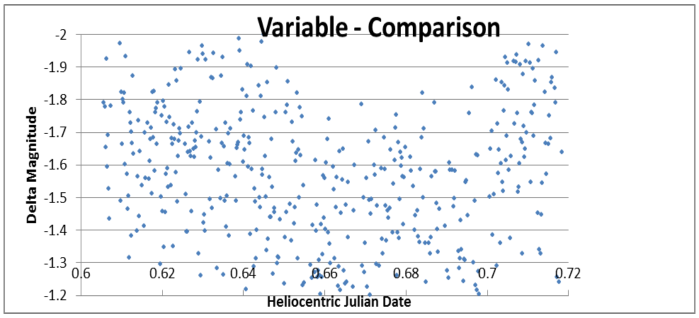

Figure 2b. WASP-33b transit data from December 7, 2012

Figure 2a illustrates a transit of WASP-33b during the night of November 7, 2011. The light curve shown in Figure 2a covers around sixty-six percent of the transit. Figure 2b is also approximately sixty-six to seventy percent of the transit for the night of December 7, 2012. The second light curve (Figure 2b) is much noisier than the first due to rapid variation in cloud coverage over the night. The transit depth estimated for the night of November 7, 2011 is approximately 0.0170 mag, while the recorded transit depth is 0.0151 mag. This difference could be due to data incompleteness, but it could also indicate the presence of another planet in the system that has changed the orbital plane of WASP-33b and increased its transit depth. More observations are needed. The second light curve illustrates a much larger change in magnitude due to a rapid increase in cloud coverage during the observations. With this cloud coverage the comparison star’s signal grew fainter until it was no longer visible in the field.

3.3 modeling exoplanets using Binary Maker 3.0

The observed exoplanet light curves were transformed from magnitude differences and Julian dates into fluxes and orbital phases and input into Binary Maker 3.0. Parameters were tested to create the best fit for the light curves produced by HAT-P-32b and WASP-33b. Binary Maker 3.0 is a computer program which generates a theoretical light curve and a three dimensional model for a binary star system, even if one of the 'stars' is an exoplanet. The observed light curve is input into the program and parameters such as temperature, mass ratio, limb darkening, and star spots can be set so the program can produce a model of the system[9].

The specifications of both the star and planet are shown in Table 2[10] and Table 3[11].

Table 2. HAT-P-32 Planet and Star Information

	Mass (kg)	Radius (km)	Temperature (K)	Period (days)	Date Discovered (In HJD)	Orbital Inclination (Deg)
Planet	0.941(±0.1666) M_J	2.037(±0.099) R_J	1888(±51)K	2.150009d	2454416.14639	88.7°(±0.6°)
Star	1.176 M⊙	1.387(±0.067) R⊙	6001(±88)K	–	–	–

Table 3. WASP-33 Planet and Star Information

	Mass (kg)	Radius (km)	Temperature (K)	Period (days)	Date Discovered (In HJD)	Orbital Inclination (Deg)
Planet	4.59 M_J	1.438 (±0.03) R_J	~ 3473K	1.21987d	2454163.22384	87.67°(±2.4°)
Star	1.495 (±0.031) M⊙	1.444 (±0.034) R⊙	7400 (±200)K	–	–	–

The masses and radii of both the star and the planet were then expressed in terms of the values for Binary Maker 3.0. The program requires the mass ratio, $q = \frac{M_2}{M_1}$, as a primary parameter instead of the mass of the two objects.

The mass ratio (q) found for the HAT-P-32b system was 0.000763. To decreases the size of the mass ratio the radii parameters were changed. The radii, for each, were found by dividing the radii by one another. This resulted in r1 (back) equaling 0.301704 and r2 (back) equaling 0.000095.These values represent the radius of a star as measured from the center of mass of the star to the point on the surface directly opposite the center of mass of the binary system, divided by the orbital separation of the system[12]. After reviewing the information in Table 2, the orbital inclination and temperature were placed as parameters in the program. The r1 and r2 (back) were increased from their originally solved values due to the program having a numerical cutoff.

Once the observed light curve was plotted further investigations were started. Some factors were changed during analysis: limb darkening and starspots. With new parameters set, a light curve was generated, Figure 3, for the HAT-P-32 system.

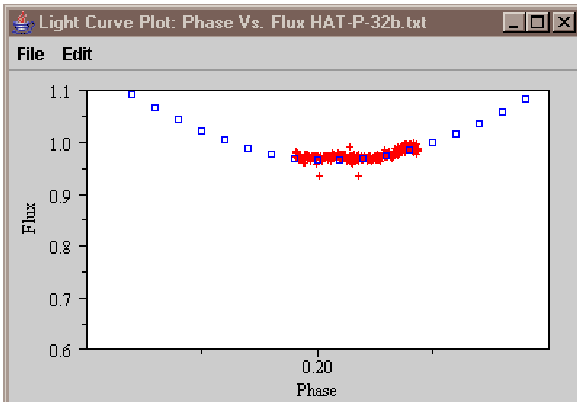

Figure 3. generated light curve for the HAT-P-32 system

The light curve in Figure 3 had limb darkening factors of 0.950 (x1) and 2.50 (x2). These values were chosen after other values were tested in the program. The larger value of limb darkening for the planet (x2) is within reasonable means because it is a large Jupiter sized planet. A Jupiter sized planet would have a limb darkening factor of around 0.9[13]. With more transit data this could be better concluded .These limb darkening factors helped bring the theoretical light curve to the values which were close to what was observed. With smaller values of limb darkening for x2, the theoretical light curve produced did not match the observed light curve as well as when the factor was increased to a higher value. In regards to starspots, two were found on the star. One spot had a colatitude of 90 degrees and a longitude of 290 degrees. The circular radius of the starspot was found to be 30 degrees with a temperature factor of 10 % or 0.10. This temperature factor means the spot is cooler than the surrounding area. The second starspot had a colatitude of 60 degrees and a longitude of 240 degrees. The spot's circular radius was found to be 12 degrees and the temperature factor was 0.0. This is very peculiar because it is unrealistic to have a starspot with a temperature factor of 0.0. HAT-P-32 is known to have a time-varying photospheric magnetic field[14] which could be affecting the way the program is deciphering the data which is creating this starspot with a zero temperature factor. Starspots were added to the system because the theoretical light curve that included them had a large dip that better matched the observations. The three dimensional model of the system is shown in Figurer 4.

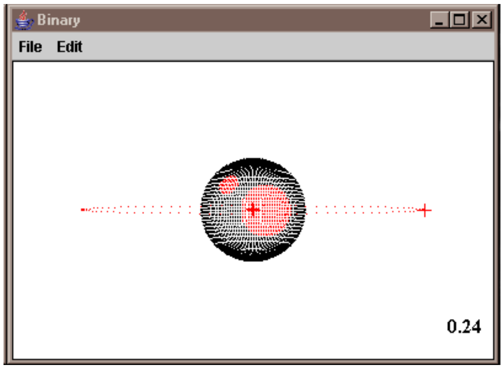

Figure 4. Binary Maker model of HAT-P-32b

Using the mass ratio formula, the WASP-33 system's mass ratio was found. Since this system has a very small mass ratio, just like the HAT-P-32 system, the radii option was used. The mass ratio found for the WASP-33 system was 0.00292 with an r1 (back) of 0.111358 and an r2 (back) of 0.000060. The values of both the radii and the mass ratio are rounded values due to the amount of significant figures the program allows the user to input. Their limited accuracy could affect the values of other factors used in finding a best fit for the light curve.

The observed light curve was plotted and analysis began. To create a best fit, limb darkening and starspots were changed. With the proper parameters set, a light curve (Figure 5) of the WASP-33 system was generated.

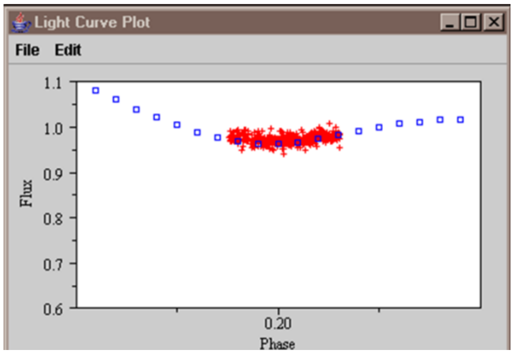

Figure 5. generated light curve for the WASP-33 system

The light curve in Figure 5 was harder to fit since the planet is located close to its parent star. This resulted in the rounded values of the radii and mass ratio. After numerous tries, the system was found to have a limb darkening factor of 2.70 (x1). Various values from the binary maker manual were tested, but this value created the best fit. In regards to starspots, only one was evident. The starspot had a circular radius of 15 degrees and a temperature factor of 1.100 or 110%. This implies that the starspot is hotter than the surrounding area it inhabits. It has a colatitude of 90 degrees and a longitude of 0 degrees. The starspot was placed in the system as it showed a fluid dip that best matched the observed light curve. This places the starspot right at the equator. Afterwards, a three dimensional model of the system was generated, Figure 6.

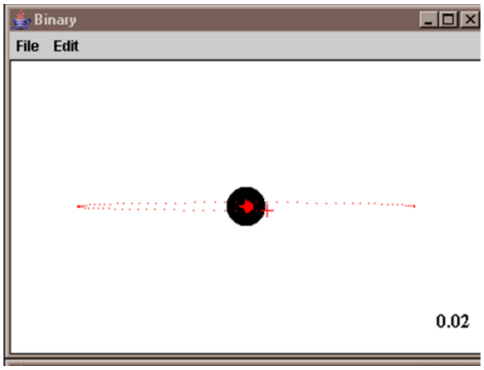

Figure 6. Binary Maker model of the WASP-33 system

The model of the WASP-33 system indicates that the starspot follows the transit of WASP-33b which could show a gradual change in the light curve since starspots are known to affect light curves, depending on the temperature factor of the starspot. When reviewing the light curve, both observed and theoretical, the starspot creates a very small transition back toward the general magnitude when the transit is finished. The starspot could be the reason behind noise as the transit approaches the end of the cycle. With more accurate transit data for WASP-33b, this model could be better analyzed again to see if starspots are creating excess noise during the transit.

4. Conclusions

Light curves provide information on the different transit depths which can relate to factors such as the size of the planet and the transit geometry. Using the light curves from HAT-P-32b and WASP-33b, transit comparisons can be made. HAT-P-32b, with a transit depth of 0.0215 mag, may be much larger than WASP-33b.On the other hand, WASP-33b possibly has the potential to be the larger planet if it is orbiting further away from the parent star, WASP-33.

The largest transit depth would result from an exoplanet crossing directly across the center of its parent star. Smaller transit depths may represent an exoplanet which is cutting a smaller chord across the surface of the stellar disk. Changes in transit depth can be a direct result of shifts in an exoplanet's orbital plane by the gravitational influence of another exoplanet in the system; this could also affect the timings of transits.

Regarding the two stars for which transit light curves have been presented, all of these possibilities are allowed by the limited number of observations. These planets have been studied by many observatories, and in fact the transit depths are due to the size of the planets. HAT-P-32b is a larger Jupiter-sized planet then WASP-33b.

HAT-P-32b did not show a great sign for another planet orbiting in the system, but there is an inclining of a second planet in the WASP-33 system. Since the second light curve (Figure 2b) exhibited noise, the result is inconclusive and more work would need to be performed to further this speculation.

HAT-P-32b was found to have an extremely large radius for a hot-Jupiter. HAT-P-32 was found to have “jitters” and is thought to be a result of a time-varying photospheric magnetic field[14]. Previous models have been created for this system using circular orbits and eccentric orbits, but no precise model was confirmed which could explain the difficulty of modeling this system within Binary Maker. Due to the high stellar jitters it was hard for modelers to make accurate models of the system. Modeling of HAT-P-32b and WASP-33b proved to be a difficult task, but the information produced can be a start for further models of these exoplanet systems.

5. Future Work

Over the course of several months new candidates are going to be studied. These candidates are being studied on the premise of possible transit timing variations. The candidates will be selected due to an increase or decrease in the O-C diagram, Transit Depth vs. Epoch diagram, and the Transit Duration vs. Epoch diagram.

6. Acknowledgements

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