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# Detection of Exoplanets Using the Transit Method

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## ABSTRACT

Differential photometry was conducted on the star GSC 3281-0800, a known host to exoplanet HAT-P-32b, using analysis software AstroImageJ. Measurements were plotted from a series of images taken during the transit, via ADU count given from an earth-based digital CCD camera. A definite light curve was established and more details about the properties of this exoplanet were discovered.

## INTRODUCTION

Exoplanets are the planets found outside of the solar system. Since the first exoplanet was discovered in 1992, a number of methods for detection have been established. This research evaluates the star known as HAT-P-32 (also catalogued as GSC 3281-0800) and its exoplanet HAT-P-32b using the transit method.

When a planet passes in front of a star, the star becomes dimmer depending on the size of the planet. The data shows a dip in flux if a planet is transiting the star we are observing, as shown in Fig. 1 (Vanderburg, n.d).

The figure shows an ideal light curve. In a real-world light-curve, the data appears more mangled and with several systematic uncertainties needed to be subtracted. This research will demonstrate the transit method way of detecting exoplanets. A free software tool named AstroImageJ (Collins & Kielkopf, 2013) will be used to obtain the necessary data to demonstrate an observed light curve from raw images.

## TRANSIT METHOD

This research was conducted using the transit method. This method relies on taking the light flux of the target star and comparing these values to other stars in the same patch of sky. The transit method is based upon several different processes that will be described throughout this paper. The most useful part of the transit method is that it may be done with a digital Charged Couple Device (CCD) earth-based camera. Based upon NASA's predicted exoplanet transit periods, a camera was set up and aimed at the target stars region of the sky and pictures before, after, and during an exoplanet's

predicted transit.

These images are then used to generate a dataset of flux values for every frame taken during the session. A downside to the transit method is that it is only effective when observing so called "hot Jupiters," which are planets that are large and close to the star during orbit and pass directly in front of our field of view from earth (Seager, 2008).

## DIFFERENTIAL PHOTOMETRY

The transit method relies on differential photometry. The idea of differential photometry is to analyze the target star's flux during our imaging session and compare it to other stars in our target star's region of the sky. Specifically, the method is

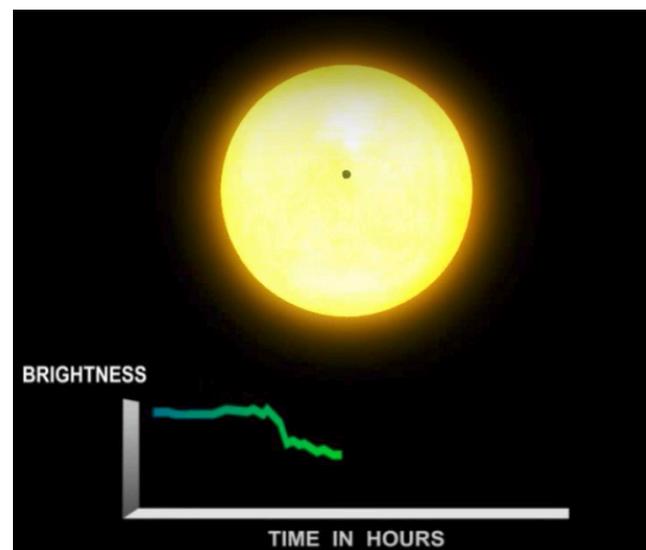
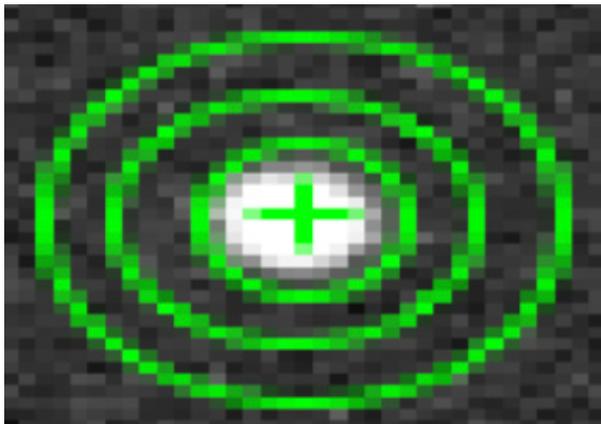


FIGURE 1. | Light curve when planet passes in front of a star.

concerned with ADU counts per pixel. An ADU (Analog to Digital Unit) count is the qualitative value of each CCD's charge output. Each pixel is impacted by a number of photons, which counts the charge and outputs it into a value. A large charge means more photons have hit the CCD pixel. Therefore, the flux may be observed from these images. However, a number of systematic uncertainties must be subtracted from the raw images obtained during the imaging session in order to accurately compare flux changes (Seager, 2008). Our data lies in the light frames, so we must calibrate the stack of images. Specifically, there are three different types of frames that need to be taken out in order to optimize our raw images. These are the bias, darks, and flat frames. Bias frames are caused by the CCD electronic signal readout during shots, dark frames are simply dark shots which can be obtained by covering the camera lens, and flat frames account for any dust smudges or inconsistencies on the camera lens itself.

## APERTURE PHOTOMETRY

Before obtaining a dataset from the calibrated images, the aperture of the target and comparison stars must be calibrated. The purpose of this is to adjust for any uncertainties located in the aperture region, such as background sky noise. The aperture region is the bright outer rings of the actual star itself. It varies in size depending on the focal length of the camera. Typically, the aperture should be set within 20 pixels of the star, and its outer region (called the annulus) must be set to 30-40 pixels. Taking the annulus's values, they are set to the apertures region, thus cancelling out any underlying uncertainties that may affect our data output (Seager, 2008). Fig. 2 shows how this looks in AstroImageJ.



**FIGURE 2.** | The second ring shows the aperture region, while the outermost ring is the calibration area.

## ANALYSIS OF HAP-P-32

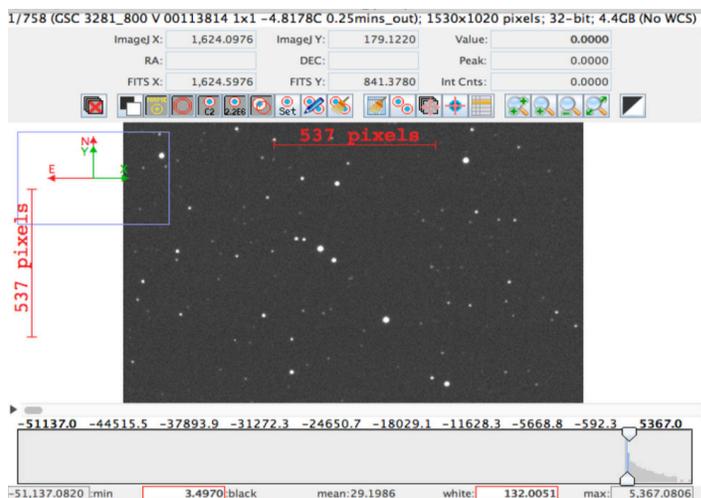
758 raw images of the exoplanet HAT-P-32b predicted transit orbit on 2016/01/17 (center of transit as predicted by NASA (<https://exoplanetarchive.ipac.caltech.edu>) in Julian Date: 2457404.65827 were analyzed. AstroImageJ was used to calibrate the images, analyze the flux of the star HAP-P-32, and fit a model onto the data.

## CALIBRATION

First, the necessary flat, bias, and dark frames used to negate the systematic uncertainties from the images were obtained.

Using AstroImageJ's image data processor, the image directories were inputted, and all 758 images were calibrated. These calibrated images were then saved to a new directory, separate from the original images. Then, they were arranged into a stack (from first to last) and input as a sequence into the program, resulting in the output shown in Figure 3.

These images were ready for differential photometry, once the aperture region was defined.



**FIGURE 3.** | All calibrated images form a stack.

## DEFINING THE APERTURE AND DIFFERENTIAL PHOTOMETRY

Now that the calibrated images were loaded into the program, the next step was to define the aperture region of our target and comparison stars. The apertures pixel range was set to the best estimate, resulting in 12 pixels for the star, 15 pixels for the aperture region, and about 35 pixels for the annulus. The software then calibrated the aperture by setting it to the annulus's ADU counts, to eliminate any uncertainties. Note that AstroImageJ automatically eliminates any faint stars in the annulus's

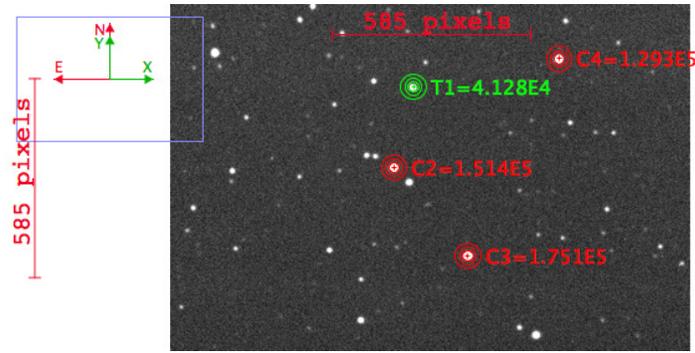


FIGURE 4. | Selected target and comparison stars

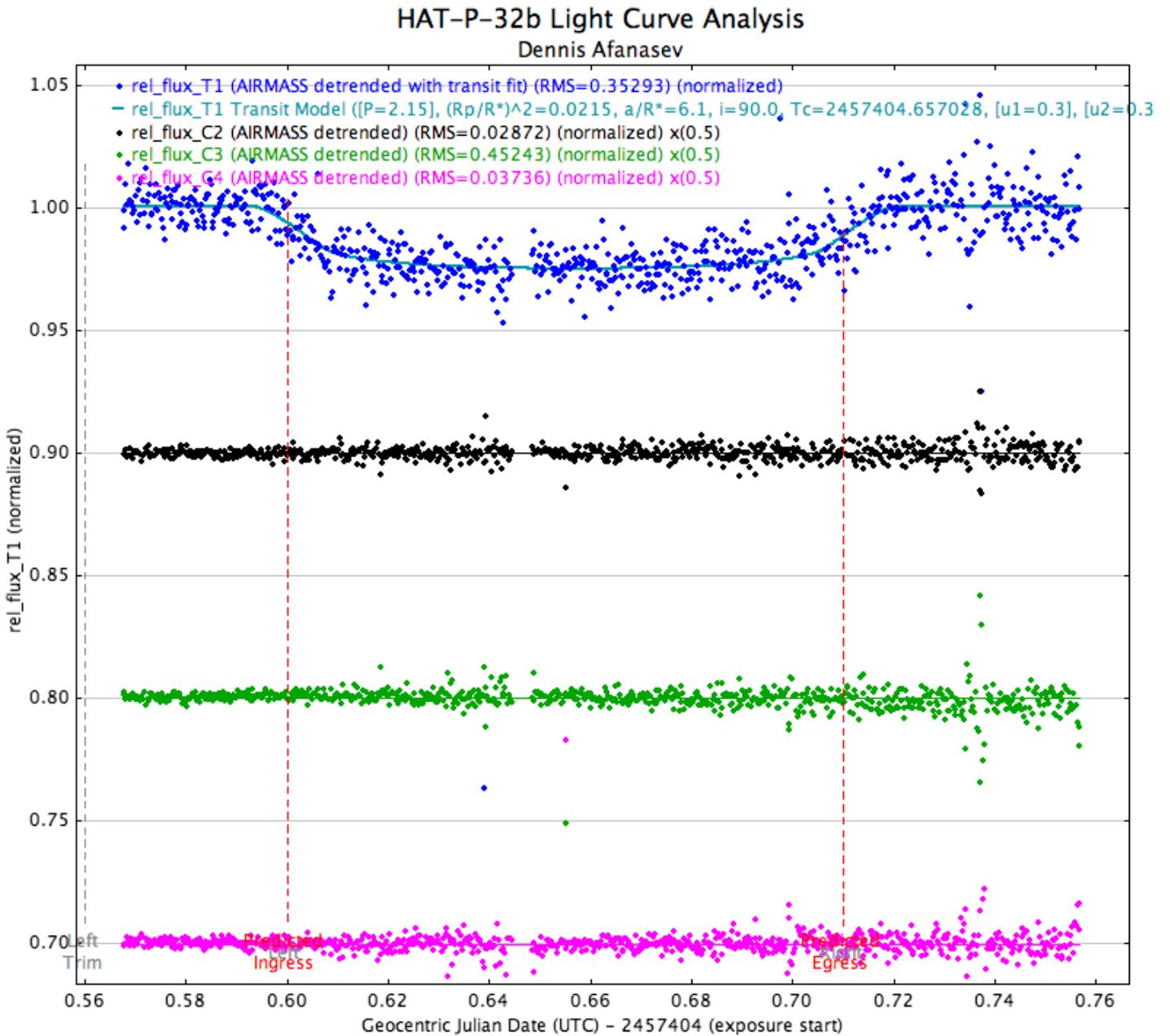


FIGURE 5. | Resulting plots of HAT-P-32b and 3 comparison stars

region. Once this is done, the target stars and comparison stars were set. Several comparison stars and one target star were, resulting in the output shown in Figure 4. The program evaluated each image in sequence and plots the flux, resulting in the results shown in Figure 5.

## PROPERLY PLOTTING THE DATA

It was necessary to specify the proper graph format in which the measurements will be displayed in the AstroImageJ plot Graphic User Interface. The beginning date of the observation was recorded in the Julian Date format and plotted along the X-axis, which was set to its representation of hours and minutes (2 decimal places.) The flux was plotted along the Y-axis. Each star's flux was normalized to points along the Y-axis of my choosing, for visualization purposes. Airmass is a set of data recorded along with the transit photo-shoot, determining atmospheric conditions and negating them from the data. It is considered an uncertainty.

## ANALYSIS OF THE PLOTTED DATA

As seen on Figure 6, the target star (labeled as rel\_fluxT1) encountered a 2.1% dip in flux as the exoplanet transits across. Notice the dispersion of the points in the target star in relation to the comparison stars. This was due to the possibility of a binary planetary system or random stellar fluctuations (Hartman, 2011). It may not fully be known exactly what the uncertainties are, but conclusions may still be drawn from the data. Notice a gap in the data at around 0.65 JD. This was due to low quality images in the calibrated stack, which had to be removed, perhaps because of faulty camera movement or other unknown technical errors. Note that the other stars' flux remains relatively linear, indicating that a large body must have passed in front of this star.

## TRANSIT FIT

AstroImageJ automatically fits a model onto the data points, from which we may learn a number of things about the exoplanet. Firstly, the host star parameters must be specified, in particular the radius (as  $R_{sun}$ ), mass (as  $M_{sun}$ ), and spectral type (F5V for HAP-P-32). From this information, a series of parameters are calculated from the shape of the light curve, such as time in transit and impact angle. These formulas were obtained from a study conducted by Seager and Mallen-Ornelas (Seager & Mallen Ornelas, 2003). Some assumptions were made for these formulas: the exoplanet's orbit is circular, and the light is from a single star. Periodicity of the planets transit is inputted manually. For HAT-P-32 it is 2.15 days. The following calculations use variables given from the input below.

$(R_p/R_*)^2$ : The transit depth (which can be expressed as a percentage) derived from:

$$\Delta F \equiv \frac{F_{\text{no transit}} - F_{\text{transit}}}{F_{\text{no transit}}} = \left( \frac{R_p}{R_*} \right)^2$$

Where  $R_p$  is the radius of the exoplanet, and  $R_*$  is the radius of the host star. A result of 2.1% was obtained from this exoplanet, which is consistent with our light curve.

$A/R_*$ : The semi-major axis in terms of the host star's stellar radii, given by:

$$\frac{a}{R_*} = \left\{ \frac{\left(1 + \sqrt{\Delta F}\right)^2 - b^2 [1 - \sin^2(t_T \pi/P)]}{\sin^2(t_T \pi/P)} \right\}^{1/2}$$

Where  $t_T$  is the total transit duration,  $P$  is the period in days, and  $\Delta F$  is the transit depth, and  $b$  is the impact angle of the transit. An amount in value of the host stars radius of 6.0993 was obtained for this respective exoplanet.

Radius of the planet  $R_p$  is calculated from:

$$\frac{R_p}{R_{\odot}} = \frac{R_*}{R_{\odot}} \sqrt{\Delta F} = \left( k^{1/x} \frac{\rho_*}{\rho_{\odot}} \right)^{x/(1-3x)} \sqrt{\Delta F}$$

Where  $k=1$  and  $x=0.8$  for main sequence stars.

The final calculated value is expressed in terms of Jupiter radii. A result of 1.85  $R_J$  was obtained for HAT-P-32.

Impact angle ( $i$ ): Impact angle of the transit with respect to our view from earth, which is derived from:

$$i = \cos^{-1} \left( b \frac{R_*}{a} \right)$$

An impact angle of 89.962 degrees was recorded for HAT-P-32b, which demonstrates a nearly straight transit across the star.

## STATISTICAL ANALYSIS

A  $\chi^2$  value (McHugh, 2013) is automatically calculated by the AstroImageJ software. For the target stars' model fit, it was a value of 1630.1119, obtained by:

$$\chi_c^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

Divided by the number of data points, 752 (our Degrees of Freedom), resulted in a value of 2.17. This was not a perfect fit for the data. This was caused by the dispersion problem discussed earlier, which may possibly be due to the host star's high jitter (Hartman, 2011).

## DISCUSSION

HAP-32-B is a close orbiting, “hot Jupiter” planet. Further research would need to be conducted to establish the exact parameters of the star’s high jitter. The observations made in this study come within close range to a separate study published in the *Astrophysical Journal* (Hartman, 2011). Although the  $\chi^2$  fit is not perfect (with  $\chi^2/\text{d.o.f.}=2.17$ ), these results can be justified by the linearity of the comparison stars’ flux.

This exoplanet is one of the largest known planets discovered. When first discovered in 2011, the results broke the theoretical limit of how large an exoplanet may be.

## ACKNOWLEDGEMENTS

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