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How EXOTIC Works

The Reduction Routine

To demonstrate how the data reduction pipeline works, this document will walk through a sample reduction of a dataset taken by a 6” telescope of the exoplanet HAT-P-32b (VMag 11.44) observed on December 20, 2017. The telescope used is part of the MicroObservatory Robotic Telescope Network operated by the Harvard-Smithsonian Center for Astrophysics.

Tracking the Star

In order to extract the host star’s emitted light, known as the flux, from images in a dataset, the first step is to locate the star on the first image, and track it as it moves throughout the subsequent images taken during the night. Telescopes themselves track the star as it moves across the night sky, but despite this, the star’s position in the image is still likely to change between images as the tracker slips or drifts slightly. In order to correct for this, after the user first enters the star’s location in the first image, a mathematical function is fitted to the shape of the star on the detector in order to find the center of the star. This fitted mathematical function, also known as a centroid, is a 2D Gaussian function that is determined using a quick model fitting routine known as a least-squares fit (Figure 1). Large shifts between images that result from a tracking slip that occurred during the observing run are also registered and corrected for automatically.

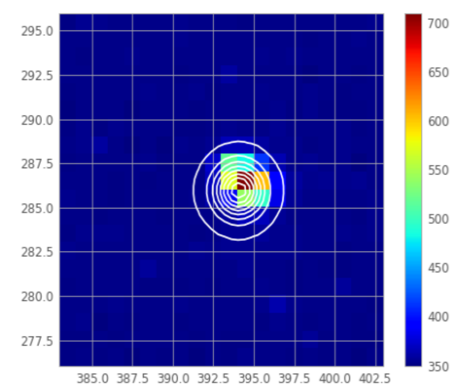


Figure 1: A subsection of a MicroObservatory Image containing the exoplanet HAT-P-32b.

To demonstrate the tracking of the target as it moves on an image, during the reduction process, plots of the X centroid position and Y centroid position as a function of time are generated. If the telescope tracking is good, the X and Y centroid positions should remain constant, unlike what we observe in this current dataset. Even though in the images below the star drifted over 250 pixels in the X direction and 100 pixels in the Y direction over the course of the example observation, the centroid was still able to keep track of it. These plots are saved as “<target name>XCentroidPos<date>.png” and “<target name>YCentroidPos<date>.png”.

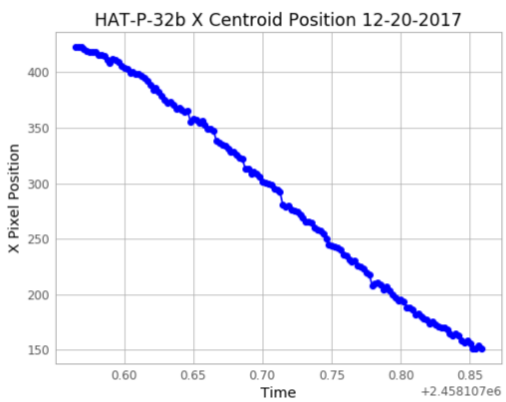


Figure 2: Centroid X Pixel Position vs Time

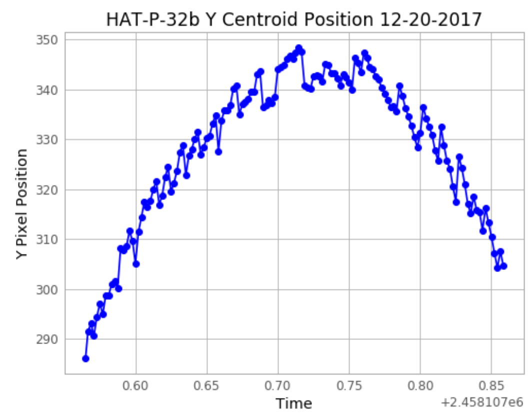


Figure 3: Centroid Y Pixel Position vs Time

Another set of produced plots that are helpful for determining the quality of the tracking throughout your image series, are the plots that are saved as “XCentDistance…png” and “YCentroidDistance…png”. These plots show the distance between the X and Y positions of the target and comparison star. If the star tracking is good, the distance between the stars should remain close to constant. As you can see in Figures 4 and 5 below, the centroid fitting routine tracked the stars well because the distance between them only changed by at most 1 pixel in either direction.

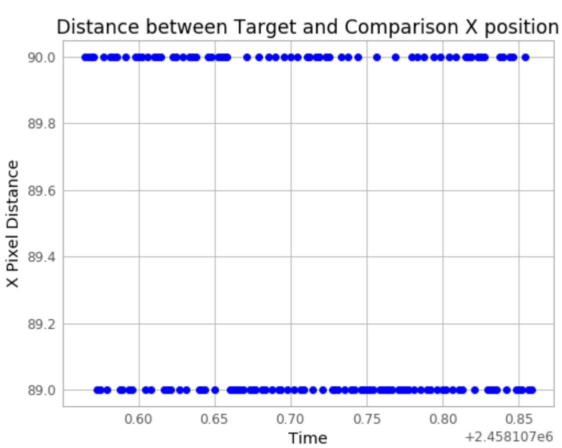


Figure 4: Centroid X Distance between Target and Comp

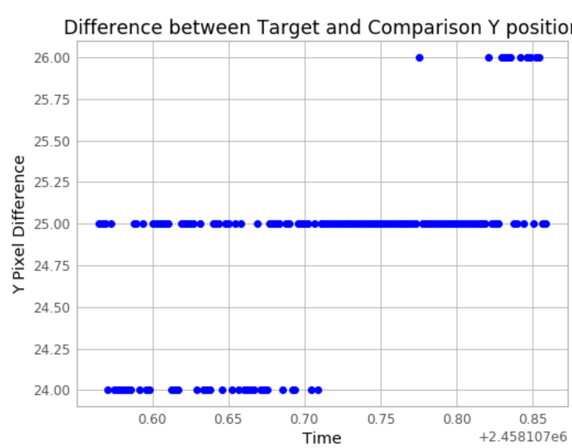


Figure 5: Centroid Y Distance between Target and Comp

Extracting the Flux of the Target

After establishing a mechanism for tracking stars throughout the image series, the next step is to determine the flux of the target star. To compute the flux, a circular aperture extraction is performed. In this method, the values of the pixels that are inside the target aperture, the red circle in Figure 4, are added together. The resulting sum is the total amount of light that was detected within the target aperture.

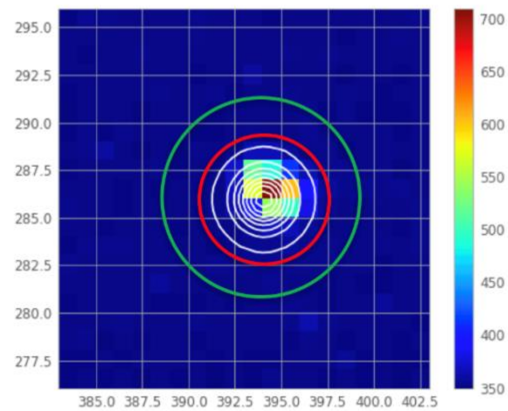


Figure 6: A subsection of a MicroObservatory Image containing the exoplanet HAT-P-32b. Target Aperture (red) and Annulus (green) for HAT-P-32b

While the target aperture sum gives the total amount of light detected within the red circle, both light from the star itself and the background light is included in that sum. In order to isolate the light from the star, a background annulus, which is the area between the red and green circles, is used to determine the average value of the background pixels (Figure 4). The average background value is then subtracted off of each pixel value inside the target area. After the background subtraction, all that is remaining is the isolated flux of the star. A plot of the target flux values as a function of time is then generated (Figure 5) and saved as “TargetRawFlux<target name><date>.png”.

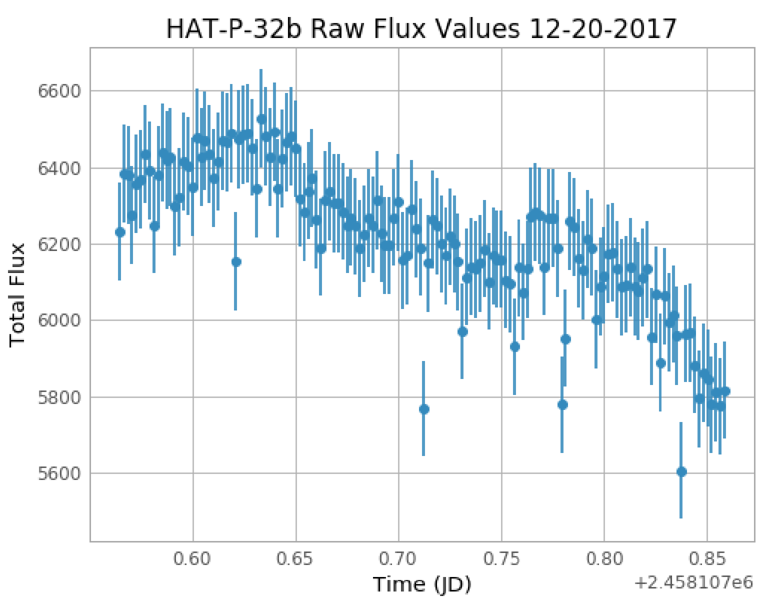
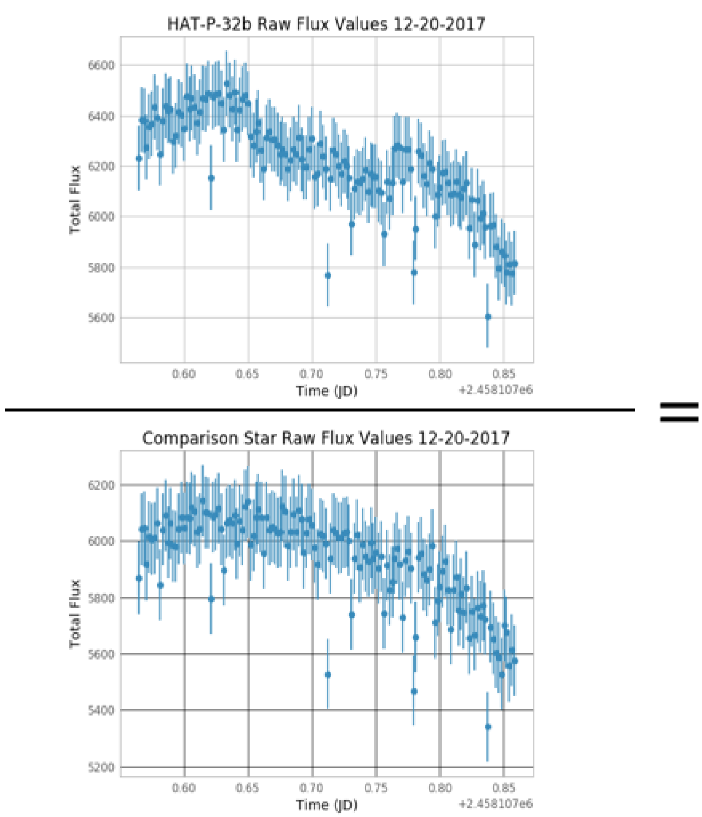


Figure 7: HAT-P-32b Raw Flux vs Time. In this example, you can actually see the transit in the raw data (between .65 and .75 jd on the X axis), before possible sources of error have been corrected for, but this will not always be the case.

Normalization by a Comparison Star

After extracting the flux of the target star, sources of error that may have been in play during the observing run need to be corrected for. To do this we want to extract the flux of a comparison star whose brightness should not change over time, and is similar in brightness to the target star. Using the same method that was used to extract the flux of the target star, the time varying flux of comparison stars, whose locations the user inputs, are recorded. A comparison star's flux should theoretically look like a flat line but as you can see in the bottom left plot of Figure 6, the flux vs. time plot of the comparison star has a similar shape to that of the target star. To correct for whatever source of error that shape is attributed to, the code divides the time varying flux of the target star by that of the best comparison star. The result is the normalized target star flux which then gets plotted as a function of orbital phase. The transit signal, which is the dip in flux that can be seen between orbital phase -.03 and .03, is now far more distinct.



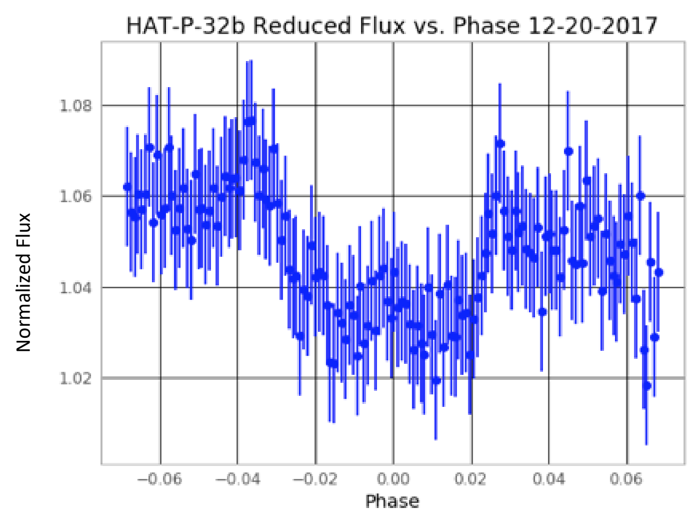


Figure 8: HAT-P-32b Normalized Flux vs. Phase. The transit occurs between -.03 and .03 phase. Gets saved as "NormalizedFluxPhase<targetName><date>.png"

A planet's orbital phase is a number that describes where the planet is in its orbital cycle. The phase is 0 when it is transiting in front of its star, ½ when it is directly behind its host star and either ± ¼ if it is directly to side. If you are in fact observing a transit in your dataset, you should expect to see a dip centered at phase = 0 in the final reduced light curve.

Determining the Optimal Aperture and Comparison Star

In the explanation of the code so far it has not yet been made clear how the aperture and annulus sizes used to extract the fluxes, and which comparison star to divide by, are determined.

If you recall the star tracking section, the centroid used to track the star between images estimates the size of the star on the image. Based on this size estimation, the code tests several combinations of aperture and annulus sizes for each comparison star the user decides to input. Then, a model light curve developed by Gael Roudier is quickly fitted to the data, and the annulus size, aperture side, and comparison star that is eventually selected is the combination that the model light curve fits best. A more thorough explanation of the light curve model is given in the subsequent section.

The Full Lightcurve Fitting Routine

Now that we have used the optimal aperture, annulus, and comparison star to completely reduce the image set into a plot of flux vs time (Figure 6), it is time to fit a lightcurve model to the data so that we can determine information about the planet.

Before delving into how the light curve model is fitted to the data, let us first look at what a lightcurve model is. A light curve model, is a mathematical function that is designed to model the shape of the transit signal of an exoplanet. There are several planetary features that can affect the shape of the lightcurve model, but the most important features are the mid-transit time, the orbital period, and the ratio of the planet's radius to that of its host star. To examine the effects these parameters have on the model, see Figure 9 below.

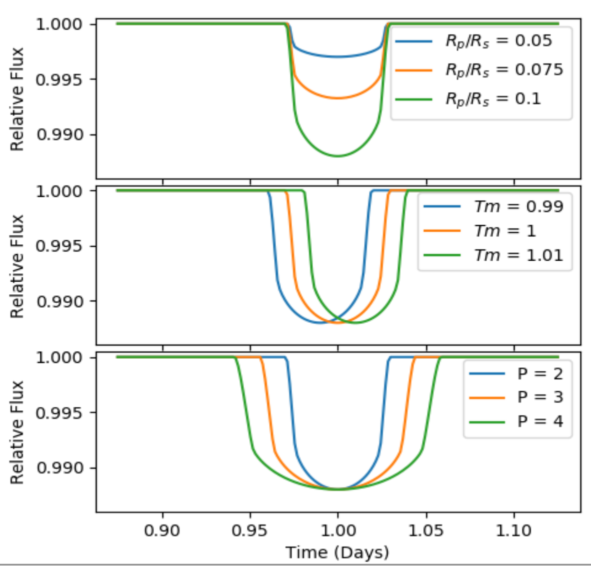


Figure 9: The top plot shows that as the ratio of planetary radius to stellar radius increases, the depth of the transit increases. The middle plot shows that a change in mid transit time shifts the model in time. Finally, as the orbital period increases, the transit signal widens.

In terms of fitting the light curve model to the data, although a quick least-squares fit is sufficient for determining the optimal aperture size and comparison star, a Monte-Carlo Markov Chain (MCMC) simulation is required to thoroughly explore the possible lightcurve fits. The MCMC used in EXOTIC fits for the mid-transit time, and the ratio of the planet's radius to that of its host star. Also, coefficients of an airmass model (model = $A*e^{B*Airmass}$) are fitted for to correct for the fact that the amount of atmosphere the star's light passes through changes as it rises throughout the night. Figure 10, which will get saved as "Traces<target name><date>.png", are the results of the MCMC fitting routine. For details on how an MCMC works, check out this resource: [MCMC Introduction]

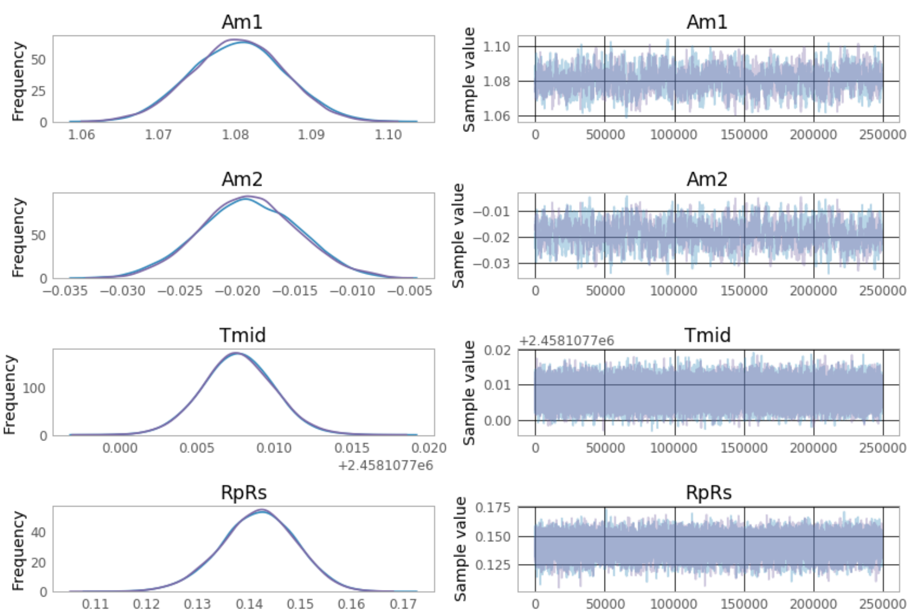
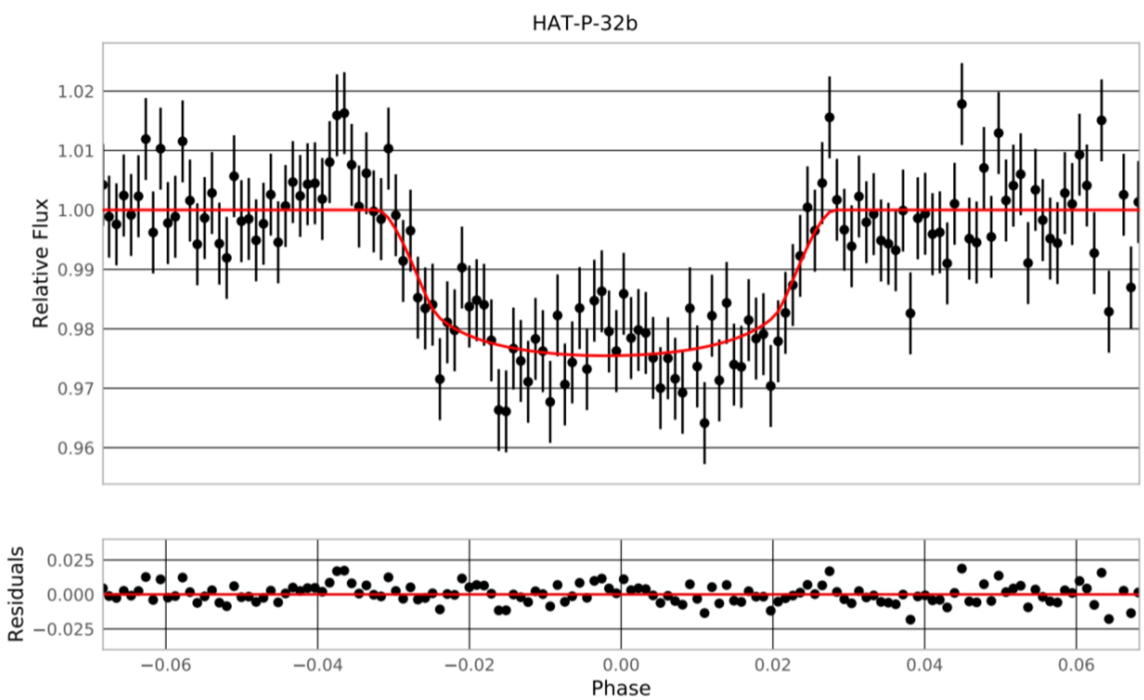


Figure 10: The results of the MCMC fitting for Transit Depth, Airmass Constants 1 and 2, and Mid Transit Time. The standard deviation of each variable's histogram is the new uncertainty on the variable.

Results Interpretation

After reducing the dataset, and fitting a light curve model to it, the final result produced by the code is a final lightcurve fitted with a model (Figure 11). The red lightcurve model shown is the result of the MCMC fitting routine described in the previous section. A good way to check the quality of the lightcurve fit is to look at the residuals of the fit, which are shown in the smaller subplot in Figure 11. The residuals are determined by dividing each data point by the value of the model at that point, and then subtracting one. The error bar sizes represent the photometric uncertainty, which is the scatter in the data that is derived based on how bright your target and comparison star are. That photometric uncertainty is then propagated through the entire reduction process, and then finally scaled based upon the quality of the lightcurve model fit (determined by the reduced chi squared metric). This means that if the lightcurve model does not fit the data well, the error bars get inflated in size.



Accompanying the final light curve, is a .txt file in which all of the results of the lightcurve fit are saved. The most interesting among the results, is the fitted ratio of planetary radius to host star radius (Rp/Rs). If you square the ratio of Rp/Rs, you get the percentage transit depth, which is the percentage of the host star's light that gets blocked by the transiting planet. This HAT-P-32 b transit has a depth of approximately 2.5%, which can be determined by looking at the y axis of

Figure 11. For reference, a Jupiter sized planet orbiting around a sun sized star will cause the observed brightness to decrease by ~1% but an Earth sized planet orbiting around the same star will only cause a dip of 0.008%.

Another fitted parameter, is the mid transit time of the planet, which can be extremely useful for increasing the efficiency of future exoplanet follow up missions by giving a better estimation on when the planet will transit in the future. The uncertainties on the fitted parameters are produced as a result of the MCMC lightcurve fitting routine. To understand how they came about, please check out the MCMC introduction link in the previous section.