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Semi-synthetic lightcurves: The effect of systematic noise in Spitzer Space Telescope observations of hot Jupiters

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Abstract

Secondary eclipse observations of hot Jupiters is one of the methods most often used to probe their atmospheres. It also allows the orbital eccentricity to be constrained. The depth of the eclipse gives information on the temperature and composition of the atmosphere and the time of mid-eclipse gives the eccentricity information. Spitzer has been the main instrument used to make these measurements to-date. These observations are strongly affected by systematic noise that must be corrected for to enable useful measurements of the eclipse depth and eclipse time to be made. We have injected synthetic eclipses into real Spitzer IRAC data at 3.6 (channel 1) and 4.5 (channel 2) microns to test two methods of recovering the depth and phase of mid-eclipse [3]. We find that the level of systematic noise on the eclipse depth is 0.013% and 0.011% at 3.6 and 4.5 microns respectively. For the time of mid eclipse we find that the error distribution is strongly non-Gaussian so a full analysis of the simulated light curve is required to determine if the orbit is significantly non-circular.

1. Introduction

Observations taken with Spitzer suffer from systematic errors. Some of these systematic errors can be corrected for e.g. Intrapixel Sensitivity Variations (IPSVs), but the origin of some are unknown. Markov Chain Monte Carlo (MCMC) methods are most often used to explore the parameter space when fitting models to these data. However, the error bars that this method gives are usually too small because they do not take into account the remaining systematic error. Here we present a new method of estimating the amount of extra systematic error in the data. Previous investigations have shown that the level of systematic error is about 0.01% [4] but it has been reported to be as much as 0.05% [2]. The goal of this analysis is to determine to what extent the systematic errors affect the measured eclipse depth and time of mid-eclipse.

2. Method

To conduct this analysis we take a flat region of the full orbit phase curve of HAT-P-2b at 3.6 and 4.5 microns and inject into it an eclipse with the same predicted eclipse depth of WASP-35b. We use two methods of recovering the eclipse depth and time of mid eclipse: 1) polynomial fitting, 2) wavelet fitting, and compare the results to a standard MCMC fitting code [1]. The wavelet fitting method is a method used to get an estimate of the red noise (from the residuals) present in the data after a polynomial fit to the data. For the polynomial and wavelet fitting we inject the eclipse into different portions of the data (4096 data points long) 10,000 times and for each simulation, calculate the difference between the input and output values of the depth of the eclipse and time of mid eclipse. This was conducted for many different decorrelation polynomials. We then ran 10 light curves from each channel through the MCMC code using the standard polynomials no-time, quadratic-position for channel 1 and no-time and linear position for channel 2. We then compare the results of the polynomial and wavelet fitting to the MCMC results.

3. Results

Figure 1 shows an example of one of the semi-synthetic lightcurves used in the analysis. It was found that there are several values for each parameter that are out by as much as 3 sigma. The reason for this large discrepancy is that the MCMC error bars are too small. The same eclipse is being fit each time into different regions of the data set so we would expect that the results should have a Gaussian distribution. To test this we calculated the p-value and rank for the results of fitting each of the 10 lightcurves for each channel for both parameters of interest. If the results are Gaussian distributed then when one plots p vs rank the results should be on a 1:1 relation. It was found for the depths and the times of mid-eclipse that the results did not have a Gaussian dristribution. We then added, in quadrature, estimates of the systematic error until we get a value that (using the Kolmogorov-Smirnov test) give a result that is close to a 1:1 relation. For the eclipse depth we find that the systematic error required is about 0.013% and 0.011% at 3.6 and 4.5 microns, respectively . However, for the times of mid-eclipse this does not work because the real distribution of the error in this parameter is not Gaussian (high kurtosis), whereas the MCMC distribution is Gaussian. Although adding a systematic error to the MCMC results can widen the distribution, it is not possible to match the shape. Figure 2 shows the distributions from the MCMC, polynomial and wavelet fits that were most discrepant for channel 1 (3.2 sigma).

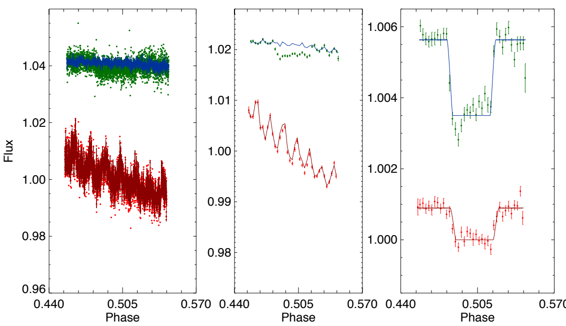

Figure 1: An example of the semi-synthetic lightcurves used in this analysis. The red data points are the channel 1 data and the green points are the channel 2 data. The red and blue lines are the model fit to the data. (left) raw data, (middle) binned raw data, (right) binned detrended data.

4. Conclusion

The polynomial and wavelet results are consistent with with the MCMC results and hence provide two independent verifications of the MCMC method. The wavelet fitting method does not improve on the polynomial method. The MCMC error bars are too small and hence there are large discrepancies between the input and fitted depths and times of mid eclipse. A systematic error of 0.013% and 0.011% at 3.6 and 4.5 microns respectively is required to be added to the error bars on the eclipse depths to give more realistic error bar values. This cannot be applied to the time of mid eclipse as the error distribution is strongly non-

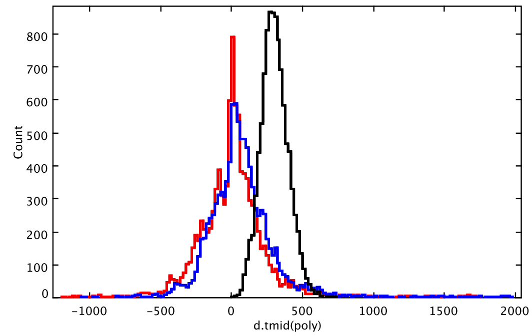

Figure 2: Distributions of the time of mid-eclipse for channel 1 the red, blue and black lines are the polynomial, wavelet and MCMC disitributions respectivly.

Gaussian. The recent work that shows the systematic error is 0.05% has not be reproduced by this analysis. These repeat observations could also be showing real variability. The time of mid-eclipse requires a full analysis of the simulated light curve to determine if the orbit is significantly non-circular.

Acknowledgements

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