A Study of the Effects of Underlying Assumptions in the Reduction of Multi-Object Photometry of Transiting Exoplanets

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Introduction

The analysis of ground-based photometric observations of planetary transits must treat the effects of the Earth's atmosphere, which exceeds the signal of the extrasolar planet. For bright, hot Jupiter exoplanets, this is generally achieved by dividing the signal of the host star and planet from that of nearby field stars to reveal a lightcurve. The question arises: what is the best way to select and treat the reference stars such that we can best characterize and remove the shared atmospheric systematics that plague the transit signal. We aim to examine the effects of several assumptions that underlie the calculation of the light curve depth, specifically the treatment of the reference stars and atmospheric systematics. Here we present a preliminary analysis of the effect of reference star choice during data reduction on the resultant lightcurve for the transiting exoplanet XO-2b. We analyze the fit of the lightcurve model for every combination of 1, 2, or 3 of the 9 selected reference star choices (refer to Figure 1). We plan to include many nights of data from a variety of exoplanets, offering unique fields with reference star choices of different brightness, spectral type, and angular distance from host star. For each data set, a light curve will be calculated for every possible permutation of the reference stars while also considering several out-of-transit assumptions (e.g. linear, quadratic or exponential). We then assess the sensitivity of the transit depths based on the spread of the values and look for characteristics that minimize the scatter in the reduced lightcurve as well as analyze the effects of the treatment of individual variables on the resultant model.

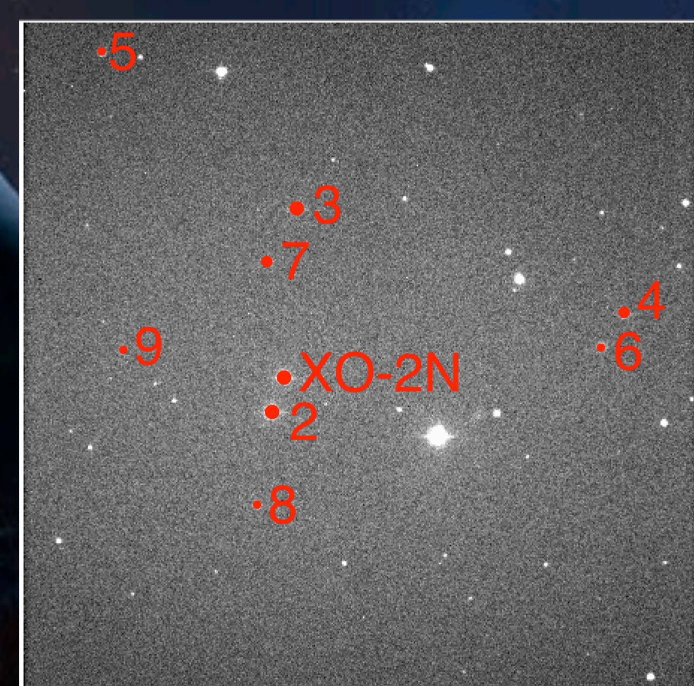
Preliminary Results

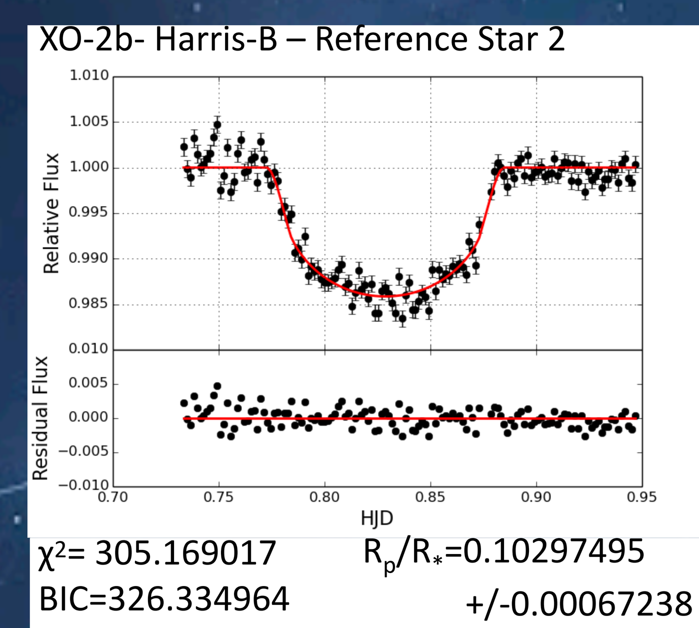
Preliminary results for the XO-2b star field indicate that the best choice of reference star(s) is to use XO-2N's companion, XO-2S. There does not seem to be any significant improvement to the scatter or fit to the lightcurve produced when only using XO-2S when compared to also including 1 or 2 other good reference stars in the reduction. It is not at all unexpected that XO-2S is an ideal candidate for photometric reductions of XO-2N, as it is the same spectral type, has a similar brightness, and is close in angular distance but physically far enough away so as not to interfere with the planetary transit. However, a recent ground based study of the system finds evidence of variability in both XO-2N and XO-2S (Damasso et al. 2015). This may eliminate XO-2S as a possible reference star choice, and the variability of XO-2N would also greatly complicate the situation. As discussed in Zellem et al. 2015, this variability can cause discrepancies in calculated parameters for the system from night to night and interfere with the ability to combine multiple nights of data.

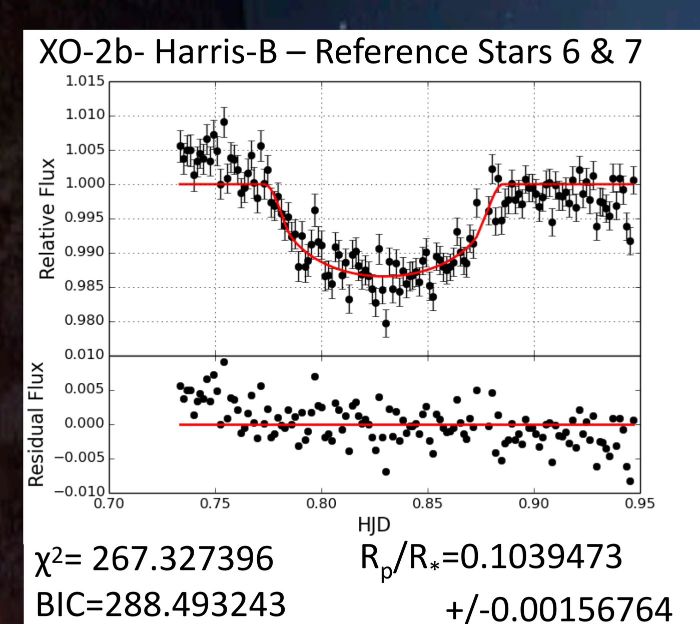
Apparent trends in the scatter and fit of the final light curves produced using combinations of reference stars that do not include XO-2N seem to indicate that the brighter reference star choices, those whose flux is closest to that of XO-2N produce the least scatter and best fit to the model. We can not yet comment on the effect of the spectral type of the reference star or the out-of-transit assumptions, as we need more observations, but hope to do so in the future. It is interesting to note that in all cases where reference star 3 has been used in the reduction, a sinusoidal effect in the light curve is produced that drowns out the signal of the transit entirely, possibly indicating a short timescale variation for reference star 3.

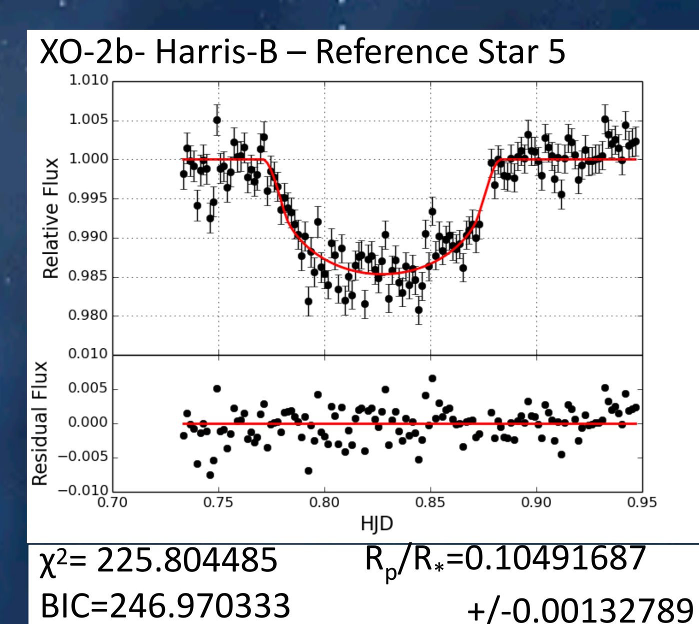
Observations

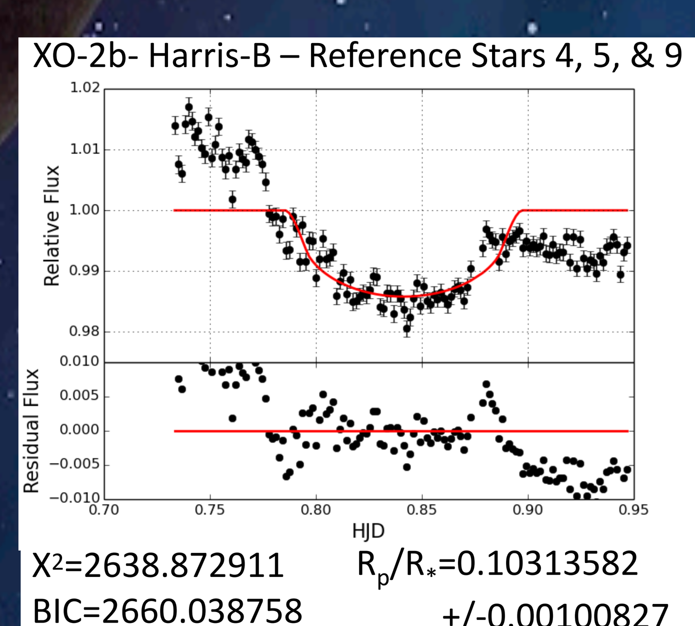
Our observations were taken using the Steward Observatory 61'' Kuiper telescope on Mt. Bigelow north of Tucson, Arizona. We used the Mont4K CCD, with a 4096x4096 pixel sensor to take photometric data in both Bessel-U (303-417 nm) and the Harris-B (360-500 nm). The Mont4K has a field of view of 9.7' by 9.7' and data was taken with 3x3 binning. Data was taken as part of a larger study on Rayleigh scattering in hot Jupiter atmospheres and thus images alternate between three 90 second exposures in the U filter and six 25 second exposures in the B filter for the duration of the transit and some time before ingress and after egress to establish a baseline. For this project's preliminary stage, presented here, we use only the B images. The weather on this night was clear with a bit of wind in the upper atmosphere, and we ranged from 1.9 to 2.1 arcsecond seeing throughout the night.

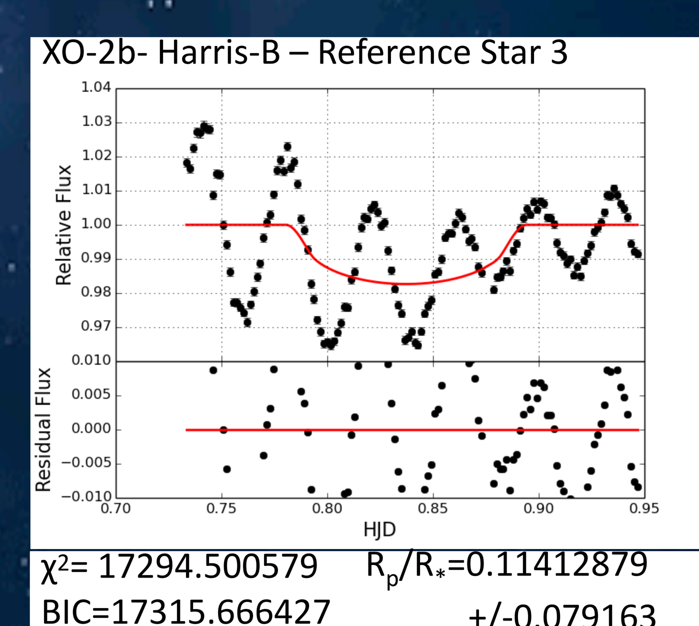












Data Reduction and Analysis

We use an in-house automated reduction pipeline ExoDRPL created by Kyle Pearson (Pearson et al. 2013) to complete the reduction for each set of reference stars. ExoDRPL generates a series of IRAF scripts to calibrate the images, using standard bias and flatfield reduction procedure. The generated scripts then perform aperture photometry, using PHOT in the IRAF DAOPHOT package. ExoDRPL measures the flux from the target star and chosen reference stars at 100 different aperture radii, ranging from 6 to 16 pixels with steps of 0.1. The pipeline chooses the ideal aperture by minimizing the out-of-transit scatter. The time varying flux of the combination of reference stars is divided from that of the host star, XO-2N to eliminate major systematics.

To fit a model to the lightcurve, we use a Mandel & Agol (2002) style fitting routine, changing the exoplanet's radius and mid-transit time, then utilizing a Levenberg-Mardquardt non-linear least squares minimization algorithm (Press et al. 1992; Mardquardt 2009) and a Markov Chain Monte Carlo (MCMC) algorithm (Ford 2005). In order to de-trend the atmospheric extinction, we use a joint-simultaneous fit of the model lightcurve and a 2nd order polynomial for which the order is determined by minimizing the Bayesian Information Criterion for each model fit. We hold Rp/Rs and the mid transit time as free parameters during analysis. The transit is modeled using an MCMC (10 chains and 200,000 links). The Gelmin Rubin statistic (Gelmin and Rubin 1992) is used to ensure chain convergence, as outlined in Ford 2006. The LM and MCMC solutions are checked for consistency f or each model, but the MCMC uncertainties are quoted as they are more conservative.

Future Study

We are currently in the preliminary stage of our investigation. As we continue, we aim to calculate and analyze light curves for all permutations of reference stars and various choices during reduction for multiple exoplanets and many nights of data. We will attempt to quantify the effect of various choices such as the treatment of atmospheric effects and out-of-transit assumptions (e.g. linear, quadratic or exponential) on the final light curve and identify the best combination of reference stars in various fields such that the scatter of the final light curve is minimized. For the XO-2b field specifically, a better understanding of the variability of XO-2N and XO-2S is necessary to make any definitive claims on using XO-2S as a reference star. It may also be interesting to determine the variability of reference star 3, as our preliminary reductions suggest it may vary on timescales as short as several minutes.

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