Exoplanet Characterization using Phase Variations Observed by TESS

Tara Fetherolf[1] (Tara.Fetherolf@gmail.com), Stephen R. Kane[1], Chelsea X. Huang[2], Avi Shporer[2], Ian Wong[2]

1. University of California Riverside, 2. Massachusetts Institute of Technology

1. Introduction

Binary systems serve as excellent astrophysical laboratories, especially in cases where two or more objects eclipse each other. The shape of the light curve in particular can be interpreted to reveal various properties of the star(s) and planet(s), such as the radius and surface temperature. The most fundamental property, the mass, is best constrained using high-resolution spectroscopy, but requires several observations over long timespans and the faintest sources are difficult to measure. Alternatively, masses can also be estimated through understanding sinusoidal variations in the light curve photometry (Shporer et al. 2011) using continuous observations over a complete orbit. We have developed an analysis program designed to detect phase variations caused by the **BE**aming, **E**llipsoidal, and **R**eflection effects (**BEER**; Faigler & Mazeh 2011). We focus on the phase variations of *TESS* Objects of Interest (TOIs) that were observed during Cycle 1, which currently includes ~100 known planetary systems and ~500 new planet candidates. Our analysis provides estimates for the companion mass and albedo, and potentially identifies false positives in the list of *TESS* planetary candidates. We also emphasize that BEER modulations encapsulate a specific type of phase variation. Therefore, we also begin to explore the astrophysical mechanisms behind other types of phase variation signals.

2. The "BEER" Effects

The best-characterized modulations that are observed in binary system light curves are caused by gravitational and geometrical influences that are periodic with the orbit of the binary system. These modulations can be separated into the beaming, ellipsoidal, and reflection effects—collectively referred to as the BEER effects (Faigler & Mazeh 2011). The beaming effect, also known as "Doppler Boosting," was first theoretically discussed by Loeb & Gaudi (2003) for star-planet systems and Zucker et al. (2007) for stellar binaries. Beaming is a relativistic effect caused by the increased intensity of light in the direction of the star's velocity. As the stellar component(s) moves along the line-of-sight, there is an associated Doppler shift causing the star's peak intensity wavelength to shift within the observed bandpass (Figure 1). The ellipsoidal effect is observed when the star(s) is rotationally synchronized with the orbital period and is gravitationally warped into an oblate shape (Figure 2). Finally, the reflection effect is caused by the primary star irradiating and heating up its companion, causing a brighter hemisphere (Figure 3). The photometric light curve we observe shows the combined result of all three BEER effects, but they can be split into three simple sinusoidal components (Faigler & Mazeh 2011). Critical characteristics of the companion can be extracted from the measured amplitudes of the BEER effects, including its mass and albedo.

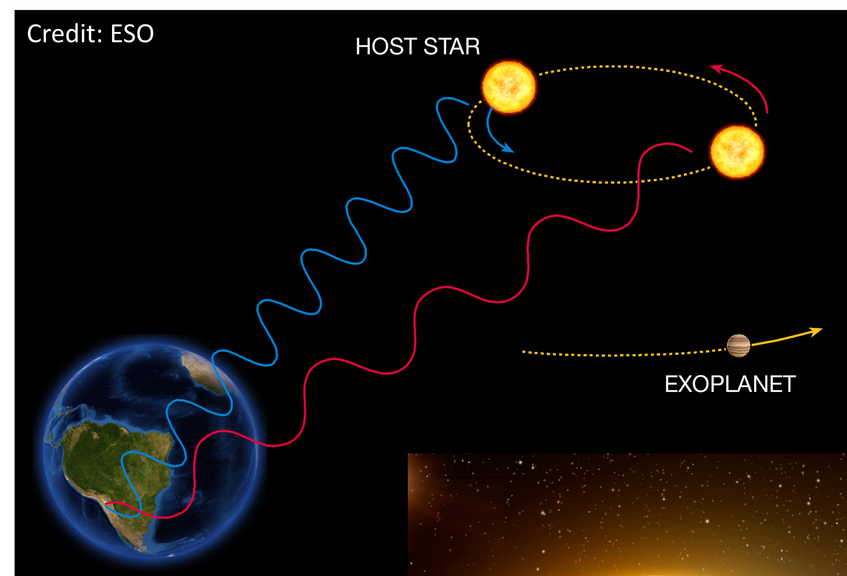


Figure 1 ↑

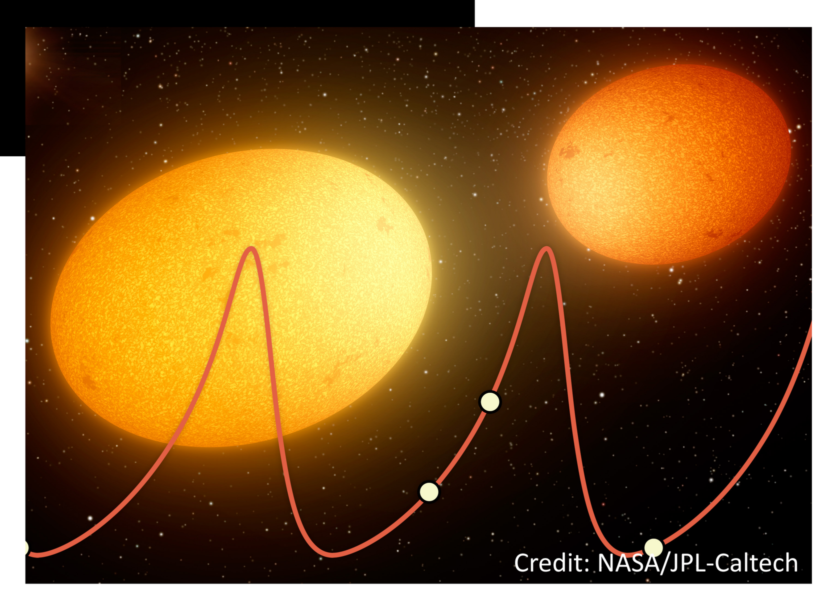
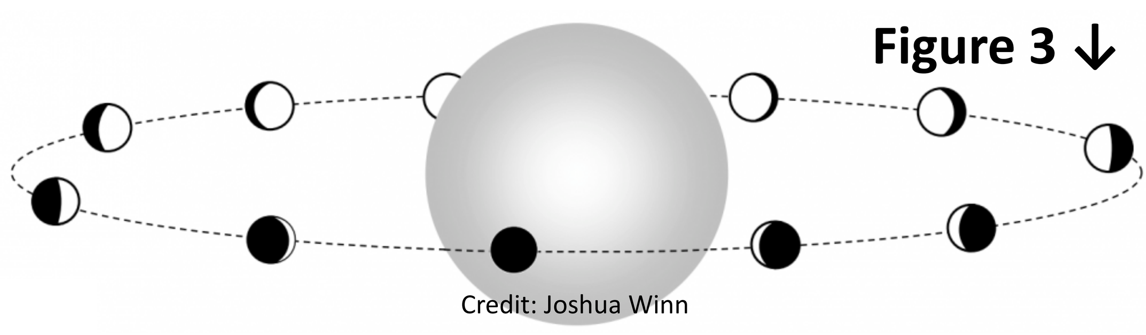


Figure 2 →

Figure 3 ↓



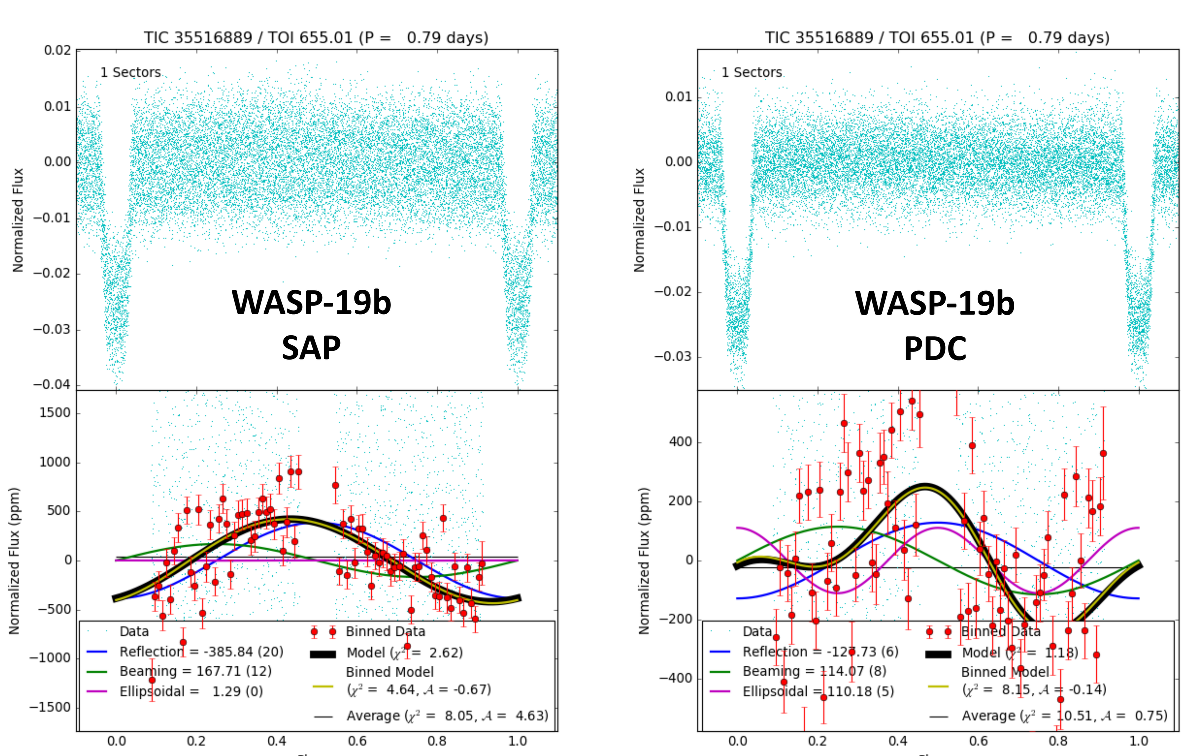


Figure 4 ↑

3. Phase Variation Modeling

The three BEER effects were first collectively used by Faigler & Mazeh (2011) to search for the presence of non-transiting binary systems in the Kepler light curves. The BEER effects have since been used to analyze phase variations of individual transiting planetary systems (e.g. Mazeh et al. 2012; Shporer et al. 2019), although generally an in-depth treatment is atypical as most exoplanet studies focus on the transit section of the light curve alone. For this reason, we developed a systematic approach to search for periodic phase variations caused by the BEER effects in the entire *TESS* planet candidate catalog. Our algorithm performs a simple normalization and detrending, removes the transit events and expected occultations, then fits a double-harmonic sinusoidal model (Sirko & Paczyński 2003) to all of the *TESS* planet candidate light curves using a least-squares minimization technique, where the leading coefficients represent the amplitudes of the BEER effects. For multi-planet systems, we trim all of the expected transit events from the light curve and separately fit the orbital phase variations for each planet candidate in the system.

Interesting phase variations are identified visually with the aid of several sanity checks, including a comparison of the results from the SAP and PDC photometry. One concern is that the detrending that is applied to the PDC photometry may remove long-timescale variations that are caused by astrophysical effects rather than systematics of the data collection (Figure 4). Considering that phase variations may not be exclusively described by beaming, ellipsoidal, and reflection effects, we also compare a 3- and 4-sinusoidal component fit (Figure 5). Finally, we search for the presence of secondary eclipses and confirm the repeatability of the phase variation fit by repeating our modeling process assuming twice the orbital period (Figure 6).

4. BEER-like Phase Variations

For systems that exhibit BEER-like phase variations, the measured **BEER amplitudes output by our algorithm can be used to analytically estimate companion masses and geometric albedos** of transiting planet candidates. From the geometric albedo we can infer atmospheric characteristics of the planets, such as estimating a planet surface temperature that appropriately incorporates the effects of the atmosphere and can be used to determine the planet's habitability more accurately than using the distance from the host star alone (Kopparapu et al. 2013, 2014). In addition to the extracted companion masses being useful for characterizing candidate planets, **the masses will also reveal the presence of contaminating stellar binaries in the planet candidate catalog**. In Figures 4, 6, and 7 we show examples of systems that exhibit BEER-like phase variation signatures: WASP-19b is dominated by the reflection component (see Wong et al. in prep. for in-depth analysis), WASP-18b exhibits both strong reflection and ellipsoidal variations (see Shporer et al. 2019 for in-depth analysis), and TOI 433.01 is a *TESS* planet candidate with all three significant BEER effects.

Figure 5 →

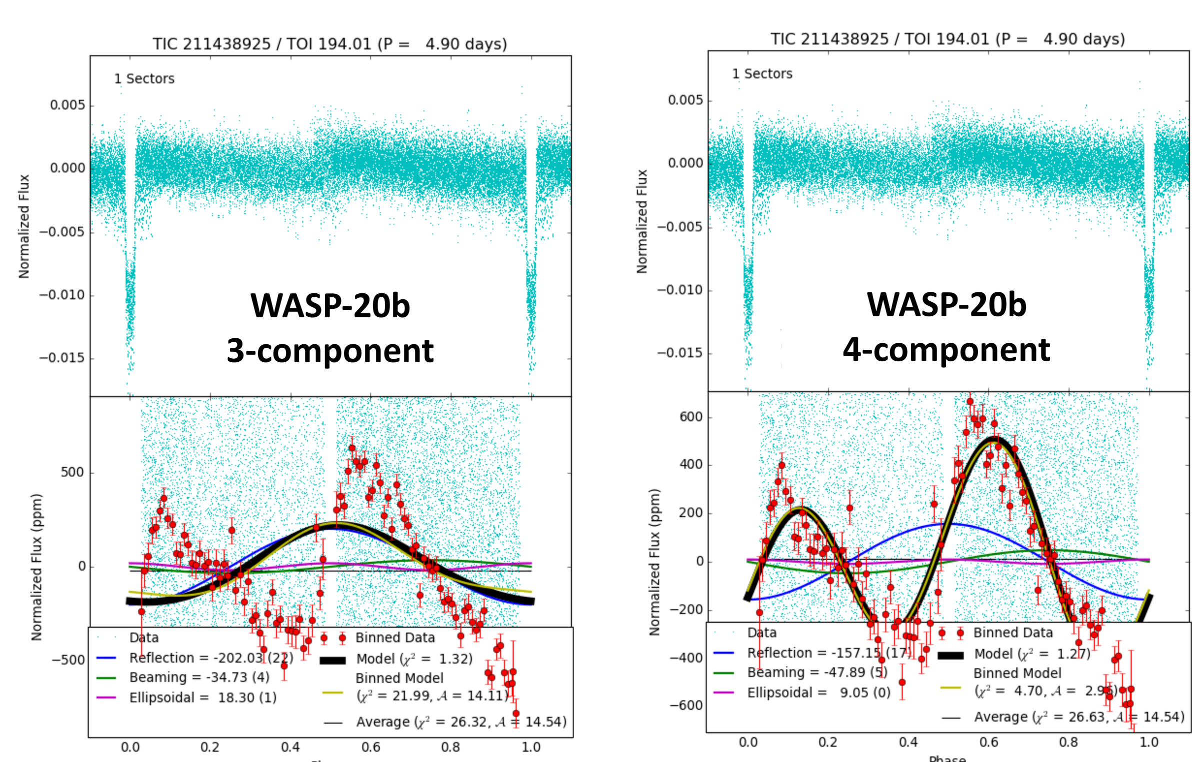
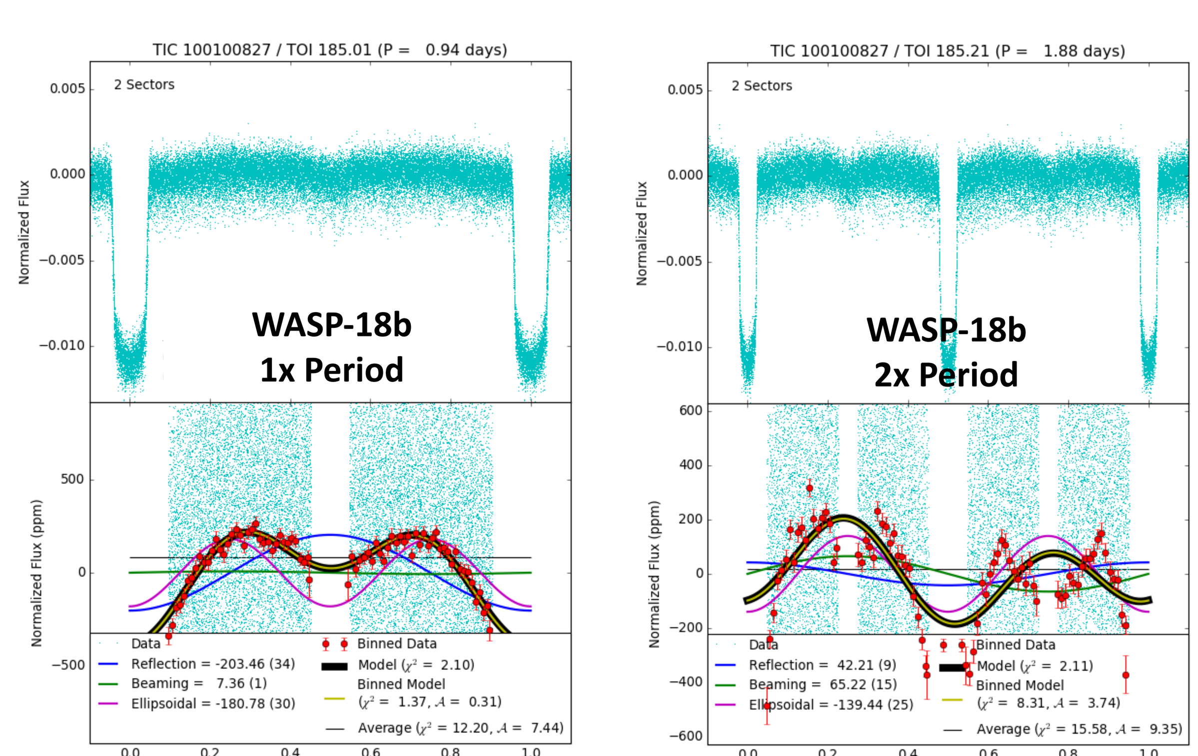


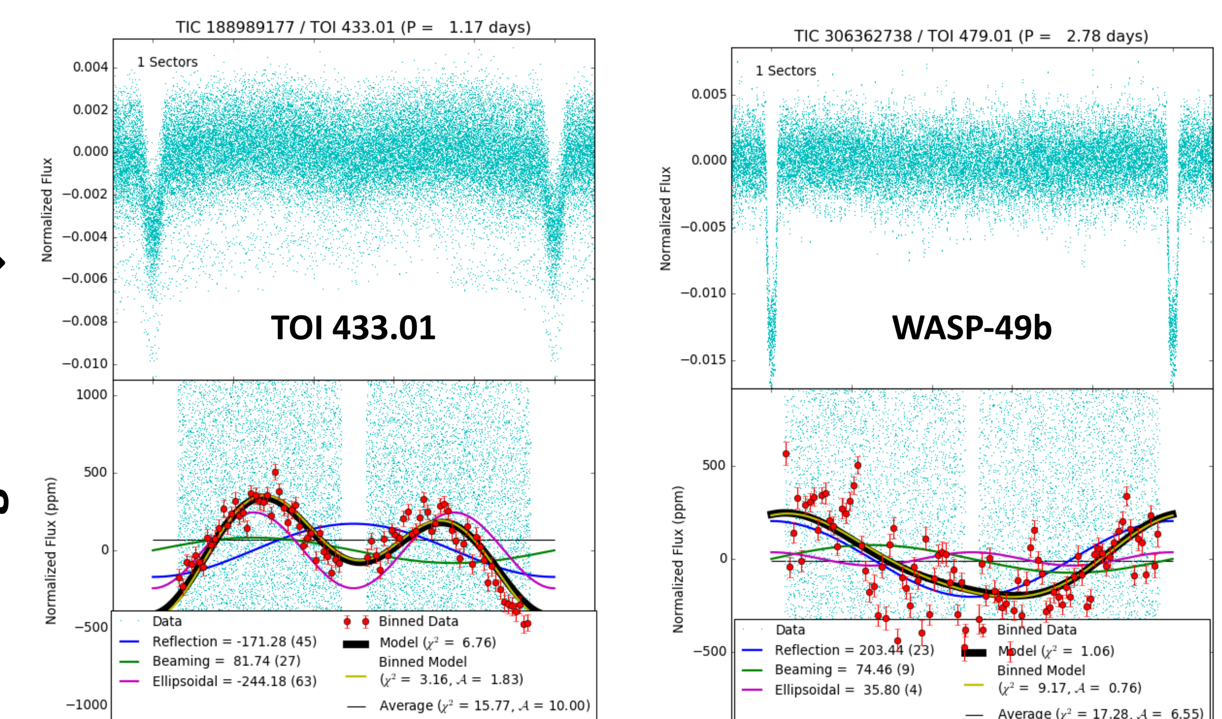
Figure 6 →



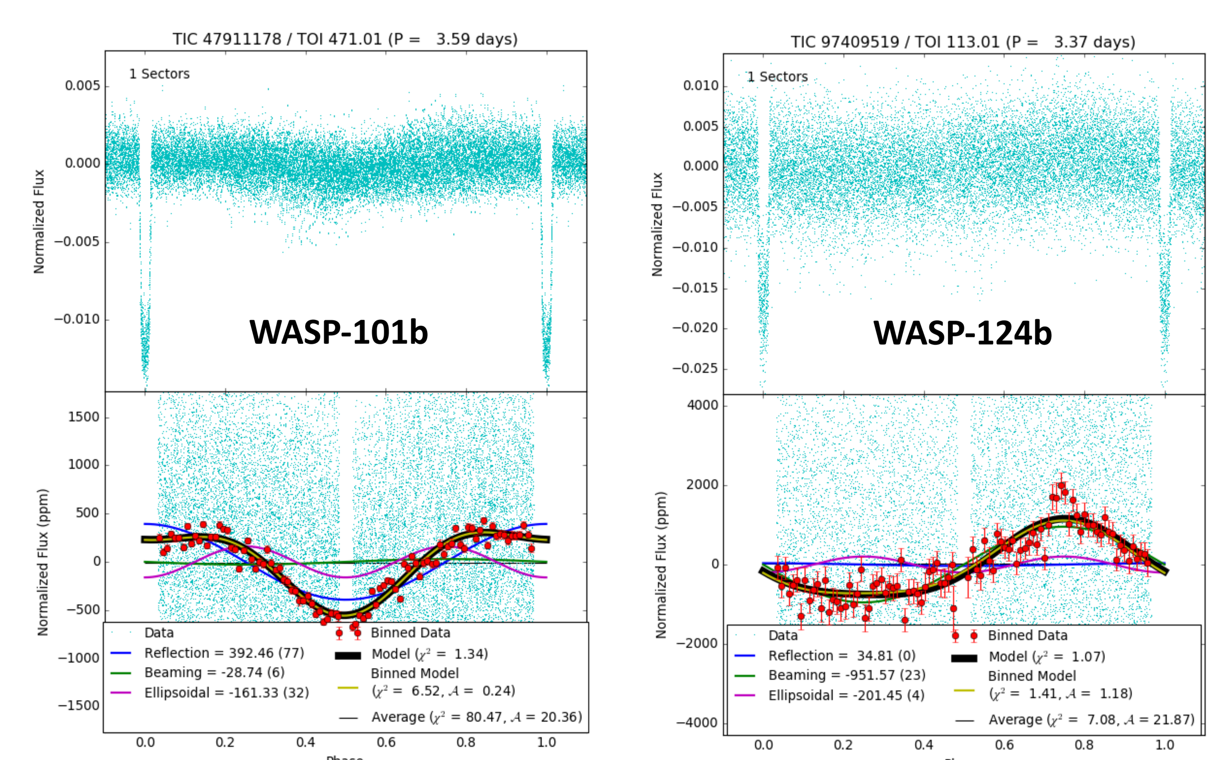
5. Other Phase Variations

One limitation to our analysis is that phase variations in general are not well-understood—especially in the case of self-luminous companions (Shporer 2017). It is important to note that BEER modulations encapsulate a specific type of phase variation. **Binary systems can exhibit many types of periodic signatures that are due to other astrophysical phenomena**, such as stellar pulsations or starspot activity. An overarching goal of our work is to develop a deeper understanding of phase variations (BEER and other types) by connecting observed characteristic shapes in the light curves with potential astrophysical mechanisms. A few examples are shown in Figures 8-10, in that the phase variations of WASP-49b, WASP-101b, and WASP-124b **cannot be explained by the BEER effects alone**.

Figures 7-8 →



Figures 9-10 →



6. Next Steps

A significant goal of our work is to investigate the reliability of companion mass measurements based on photometry alone. Therefore, we are currently focusing on the TOIs that are previously confirmed planets in order to directly compare published radial velocity mass measurements with estimated masses based on the amplitudes of the beaming and ellipsoidal effects. We will also use the amplitude of the reflection component in order to constrain geometric albedos that can be used to characterize the atmospheres of confirmed planets. In follow-up, we will apply our methodology to the greater *TESS* planet candidate list with the intent to incorporate our phase variation analysis into the *TESS* vetting process. Finally, we will prepare a user-friendly version of our code for public release, such that the community can quickly look at the BEER phase variations, the estimated companion mass, and atmospheric characteristics based on any input light curve(s).

7. Summary

The primary outcomes from this work include the following:

- **Constraining exoplanet masses and atmospheric** properties using the best-fit phase amplitudes.
- Investigation into the **reliability of photometric mass measurements** by comparing with radial velocity mass measurements.
- Integration of our phase variation analysis with the *TESS* **planet candidate vetting** process.
- Understanding systematic and **astrophysical causes behind atypical phase variation signatures**.

Faigler, S., & Mazeh, T. 2011, MNRAS 415, 3921 · Loeb, A., & Gaudi, B. 2003, ApJL, 588, 117 · Mazeh, T., et al. 2012, A&A, 541, 56 · Shporer, A., et al. 2011, AJ, 142, 195 · Shporer, A. 2017, PASP, 129, 072001 · Shporer, A., et al. 2019, AJ, 157, 178 · Sirko, E., & Paczyński, B. 2003, ApJ, 592, 1217 · Zucker, S., et al. 2007, ApJ, 670, 1326