A PILOT STUDY FOR AN ECONOMICAL MULTI-BAND NEAR INFRARED TRANSIT FOLLOW-UP SURVEY OF TESS EXOPLANET CANDIDATES

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Abstract

We present the results of a pilot survey to test the efficacy of varying observing strategies on constraining the false positive rate of large exoplanet candidates discovered by the Transiting Exoplanet Survey Satellite (TESS). We measure three simultaneous light curves in each of the J ($\lambda \approx 1.2\,\mu\mathrm{m}$), H ($\lambda \approx 1.6\,\mu\mathrm{m}$), and K ($\lambda \approx 2.2\,\mu\mathrm{m}$) bands for four known transiting exoplanets. We discuss in this paper the strategies we've employed to limit sources of systematic noise such as a variable sky background, subpixel sensitivity variations, and imperfect reference stars. For our first target, we achieve a photometric precision of $\sim$1% in the J-band, and fit the transit depth and duration finding good agreement with the literature.

1. Introduction

The *Kepler* mission began a revolution in exoplanet science, discovering thousands of exoplanets when only twenty years before it was not even known whether exoplanets existed. The mission yielded statistical studies of exoplanets for the first time in history which allowed astronomers to understand the true ubiquity of exoplanets in our Galaxy (Fressin et al., 2013; Petigura et al., 2013; Dressing & Charbonneau, 2015). The *Kepler* spacecraft accomplished this feat by searching for transits, which are small dips in the apparent brightness of a star caused by a planet's shadow as it orbits between our line of sight and the star. *Kepler* measured these transits with incredible precision. However, *Kepler* was too successful; because so many of the discovered planet-hosting stars from *Kepler* were too dim or far away, nearly half of the exoplanet candidates *Kepler* has discovered are doomed to remain candidates. The follow-up studies required to confirm the existence of these planets are too resource-intensive.

The Transiting Exoplanet Survey Satellite (TESS) is *Kepler*'s space-based successor mission that also takes advantage of the transit method to detect exoplanets, but seeks to avoid the above issue with *Kepler* by focusing its attention on nearby, bright stars (Ricker et al., 2014). This design encourages ground-based campaigns to further study its exoplanet discoveries. Because of its decision to study nearby stars, TESS will invariably observe a larger fraction of M dwarfs, which are cool stars that have radii between one-tenth and one-half that of the Sun, as opposed to *Kepler*, which focused mainly on hotter Sun-like stars. M dwarfs provide an advantage in transit surveys because it is easier to detect planets that orbit around them. Because M dwarfs are smaller, a transiting exoplanet will block a larger *fraction* of light from an M dwarf than it would around a larger star such as the Sun making a transit signal easier to detect around the former.

Despite TESS's focus on bright stars and M dwarfs which make follow-up programs easier, ground-based studies still suffer from one major disadvantage – the Earth's atmosphere. The atmosphere bends and distorts starlight as it travels to the telescope, randomly changing the distribution of star light across the detector. These changes produce variations in the photometry that hinder ground-based telescopes' ability to perform with high precision. *Kepler* and TESS are in space, so don't have to deal with this issue, resulting in incredible photometric precision. However, a recent development in technology, beam-shaping diffusers (discussed below), have allowed ground-based observatories to obtain similar photometric precision as seen by space-based observatories such as *Kepler* (Stefansson et al., 2017).

Beam-shaping diffusers are an optical component that can be added to a telescope's light path to smear light out from stars in a controlled pattern when taking an image. By blurring the image of the star, diffusers wash out the effects of the atmosphere that normally work to hinder this measurement. In addition, the starlight is spread across a bigger area on the detector which helps to mitigate any effects that could be caused by imperfections on the detector itself. Since these imperfections, like the effects of the changing atmosphere, add variation into the photometric measurements, beam-shaping diffusers mitigate this variation by averaging over larger areas of the detector. In essence, the use of diffusers trades image quality for precision photometry. This enables transit detections from smaller exoplanets.

Beam-shaping diffusers are of particular interest for near infrared detectors because their pixel sensitivity is less homogeneous than their optical counterparts, making high-precision transit work otherwise quite difficult. However, this wavelength is optimal for TESS follow-up observations because M dwarfs are brighter and more easily observed in the NIR than in the optical. Although most of the planned TESS follow up surveys use optical wavelengths, the abundance of M dwarfs demand an optimized TESS follow-up survey to observe transits at Near-Infrared ($\lambda \sim 1 - 2\,\mu\mathrm{m}$) wavelengths.

In this paper we discuss a pilot study for implementing such a survey. In §2 we discuss the observations and the strategies used to deal with the challenges of observing at Near-Infrared wavelengths. §3 discusses our analysis and preliminary results from our data, and §4 discusses the implications of our work so far, and the applicability of such a survey.

2. Observations

For this study, we present the data and analysis of the transiting exoplanet WASP-80b. WASP-80 is a star of spectral type K7V, and has a magnitude J = 9.2. All data obtained in this study were taken with the 2MASS camera (Skrutskie et al., 2006) mounted onto the Minnesota 60-inch (1.52-meter) telescope at Mt. Lemmon. The retired 2MASS camera contains three 256×256 pixel NICMOS3 HgCdTe arrays. The camera is designed such that three images are simultaneously observed, one in each of the $J-$, $H-$, and $K-$bands. This optical setup results in a 7.7'×7.7' field of view and a plate scale of 1.8" pixel^{-1}. The data were taken over the course of several nights, from 5/29/2018−6/3/2018. Most nights were photometric, though there was slight cirrus on the night of 5/30/2018. Twilight flats were taken on the night of 5/30/2018, and applied to each night of the observing run.

To approximate the effects of a diffuser, we defocused the telescope so that starlight was spread across an approximately 16 pixel diameter, resulting in a full-width half-maximum (FWHM) of ∼30". This large FWHM helps to reduce the systematics from intra-pixel sensitivity variations, but introduces more sky background in the process. An ideal survey would have a smaller pixel scale so that less sky background is introduced in the light curve. To compensate for airglow and temporal variations in the sky brightness, we dither our observations by ∼1' every two minutes, taking 15 second exposures. The exposure time was chosen to avoid saturation due to high sky background in the K band, and the dithering cadence was cho-

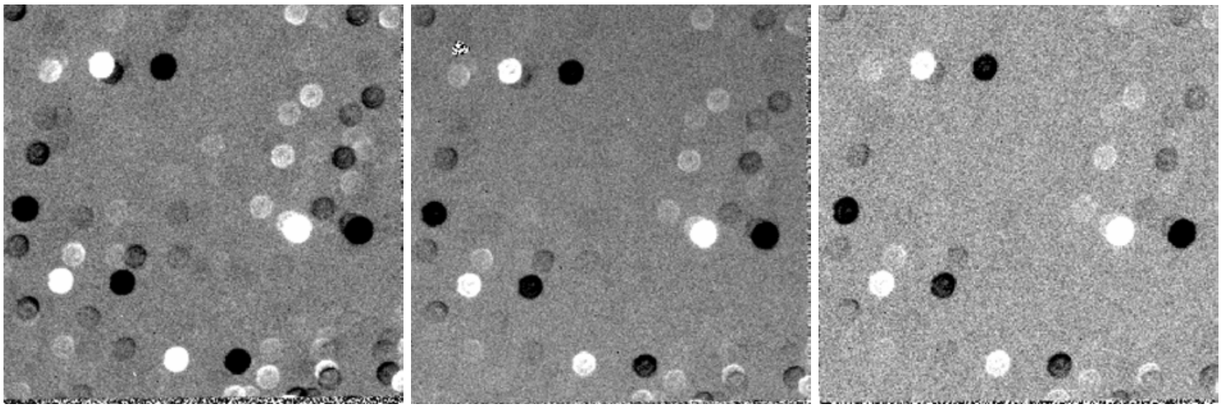

Figure 1: *Left:* Typical J-band reduced image of Wasp-80 used to measure the light curve. *Middle:* Typical H-band reduced image of Wasp-80. *Right:* Typical K-band reduced image of Wasp-80. The analysis and observing strategy is apparent in each of the images. The dark spots are negative fluxes where 10 dithered exposures within two minutes of the exposure were subtracted from each individual image to reduce errors caused by temporal variability in the sky brightness. It is plain to see the increased signal-to-noise in the J-band image in the form of stars that are not buried by noise, where the sky has the least impact. It is also apparent to see the pupil image of the stars, as the light from the stars themselves are spread across a large area.

sen to adequately sample the temporal variation of the thermal sky background and airglow lines, which are known to change on timescales of a few minutes.

3. Results and Analysis

The NICMOS arrays utilized in the 2MASS camera have quantum efficiency variations of 15–20% across the face of the detector. Thus, the measured flux for starlight on the detector is strongly correlated with the location that the star light lands on the detector. Because of our dithering strategy, this would result in pixel-level correlated flux. To correct for this effect, we took 200 twlight flat field calibration frames, which we combined into a master frame by subtracting successive pairs of flats with different median fluxes, leaving behind only the detector response in each pixel. A master flat-field image was created for each of the J, H, and K bands. Each image was processed by subtracting off the average of twenty images, ten images taken each before and after the image of interest, thus allowing for a decent measure of the sky brightness for us to remove from the image. The background-subtracted images are then flat-field corrected to remove any residual effects of large scale quantum efficiency variations.

We performed aperture photometry on the reduced images. To measure the position of the stars in the image, we first build up a template of a stellar point spread function (PSF) by co-adding the stars in the first ten images. This template was then cross-correlated with the image to determine the pixel locations of the stellar PSF. We perform photometry using the `photutils` package (Bradley et al., 2016). Ideally, the aperture is chosen so as not to include any flux contamination from nearby or overlapping stars. However, because of our large stellar PSFs ($\sim$30"), we are unable to avoid contamination from a nearby star to WASP-10. Instead of avoiding the contamination, we elect to include the contamination in the aperture, which we assume to be constant and subtract out of the light curve based on the flux ratio implied by the magnitude difference in J between WASP-10 and its neighbor, which

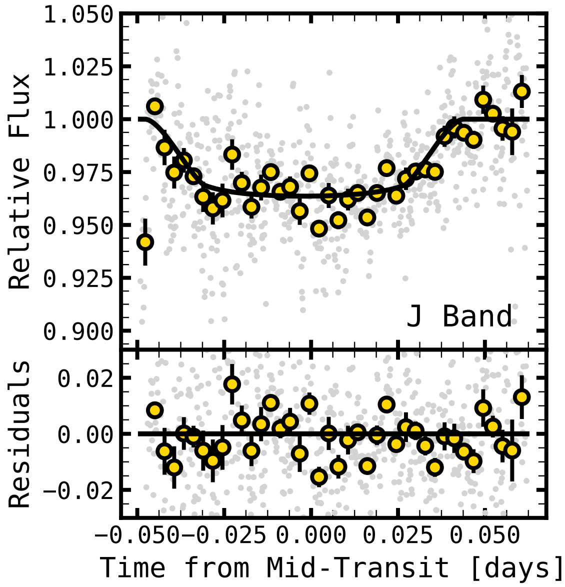

Figure 2: J-band light curve of the transit of Wasp-80b, showcasing our preliminary results. The top panel shows the light curve while the bottom panel shows the residuals of the model fit. The gray points are the flux taken from 15 second exposures. The yellow points are the brightness binned on 2 minute timescales with error bars shown. The black line is the model fit. We find good agreement with our transit fit to that of the literature, suggesting that the survey outlined above is a viable option for studying TESS planet candidates in the near-term future.

is reported by 2MASS (Skrutskie et al., 2006). We choose a circular aperture with a diameter of 18 pixels, as we find that this size aperture minimizes the point to point scatter in the light curve. We find the best results using only one reference star to account for transmission variability in the atmosphere throughout the night. We then model the out of transit flux as a second order polynomial with a dependence on airmass, which we remove from the light curve.

The light curve is modelled with the Mandel & Agol (2002) model using the transit modeling package `batman` (Kreidberg, 2015). Using an initial parameters from Triaud et al. (2013). We hold the period fixed, and vary the transit depth, duration, and midpoint using a Levenberg-Marquadt least squares algorithm. The transit parameters derived from this work show good agreement with the literature.

4. Conclusion

We present the preliminary results to a pilot study to test the viability of performing a mutli-band transit follow-up survey with NICMOS3 arrays. This may prove an economical method for obtaining near-infrared transit depths for TESS exoplanet candidates. Because this muti-band strategy provides useful information to test for false positives, such a survey has a unique niche, and value to the greater exoplanet community. In this work, we give the limitations of our work, and their applicability for this purpose, finding plausibility that such a survey can be successful.

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