No Planets Left Behind: Single Transit Candidates from K2 Campaign 19

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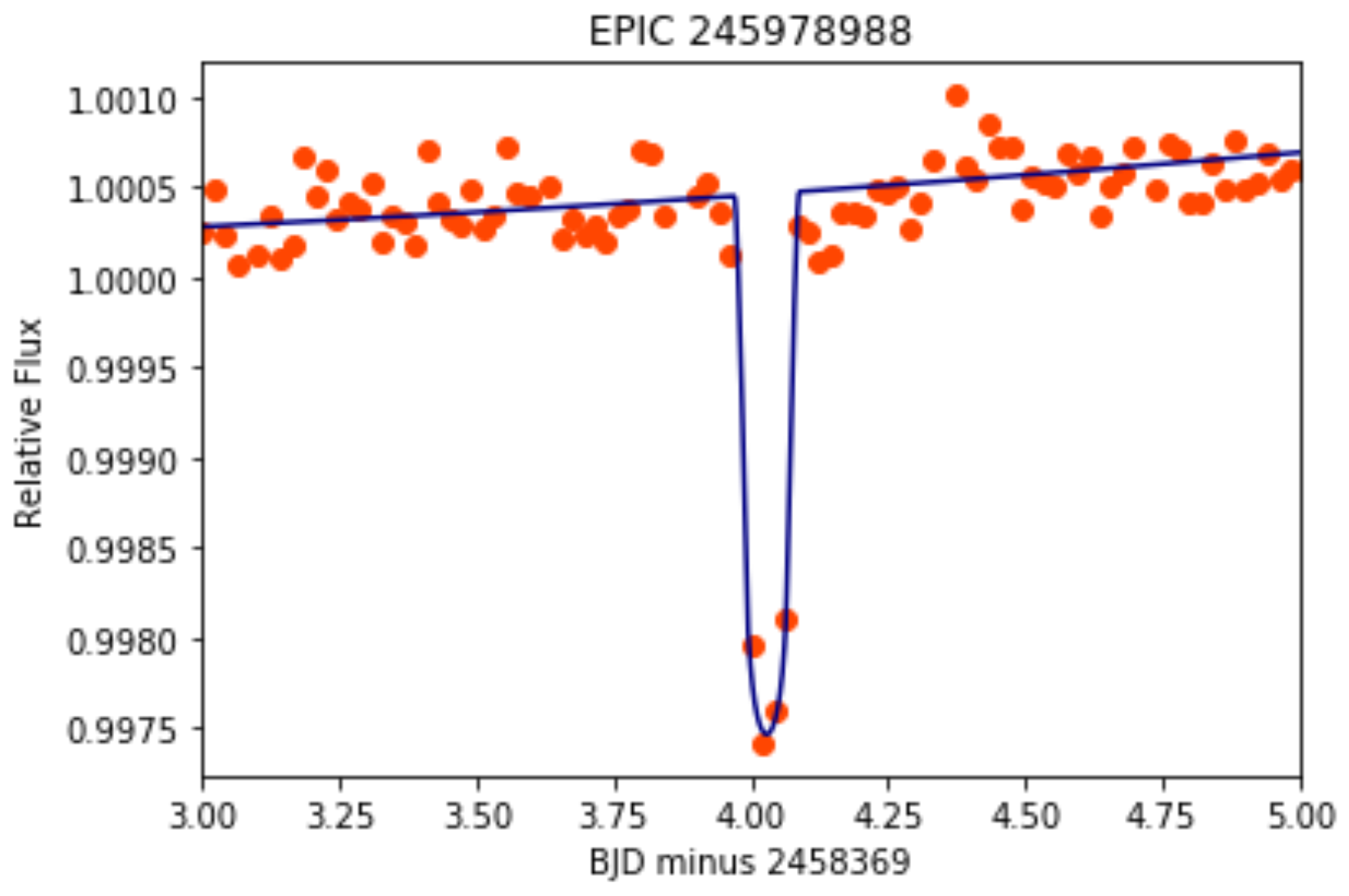
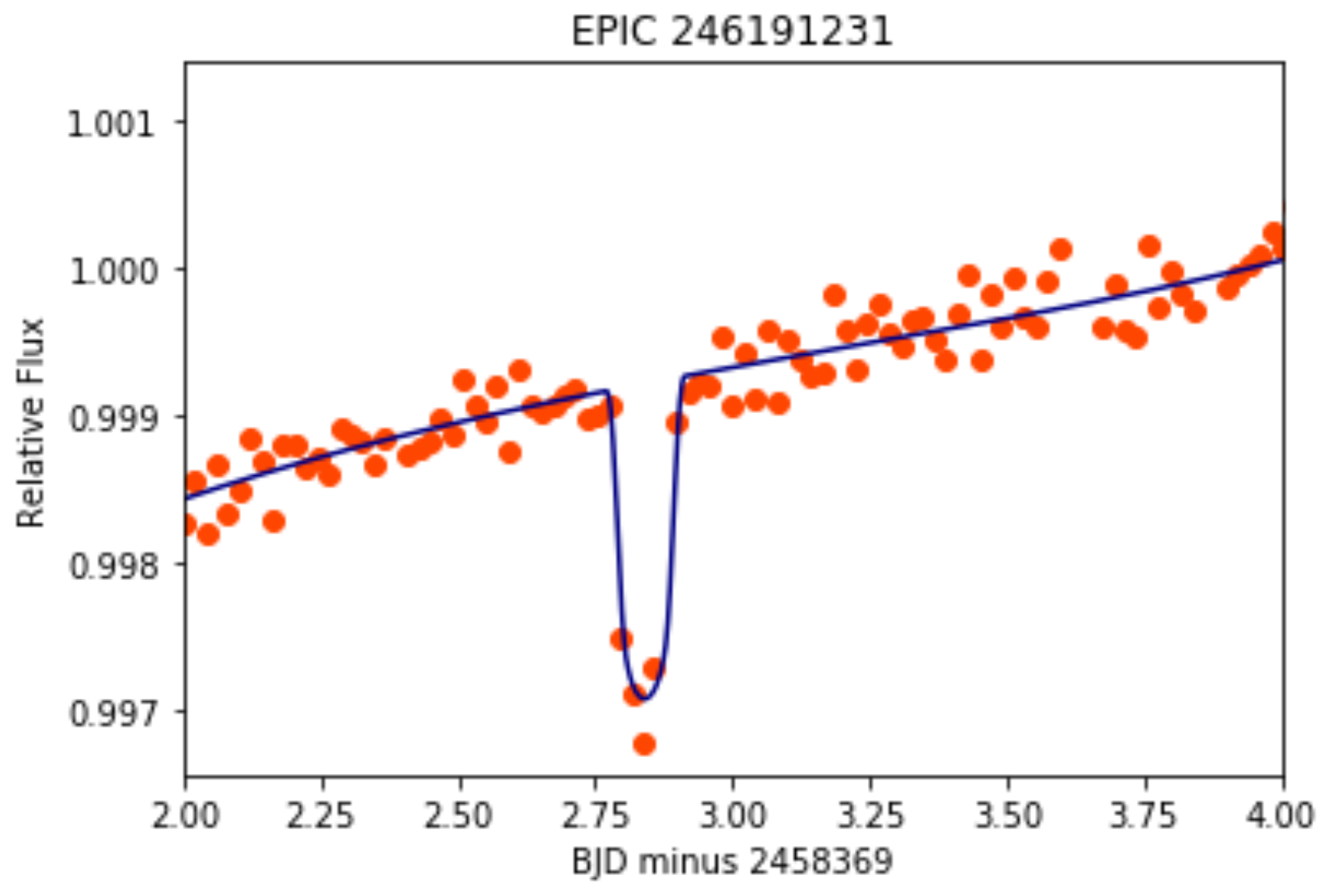
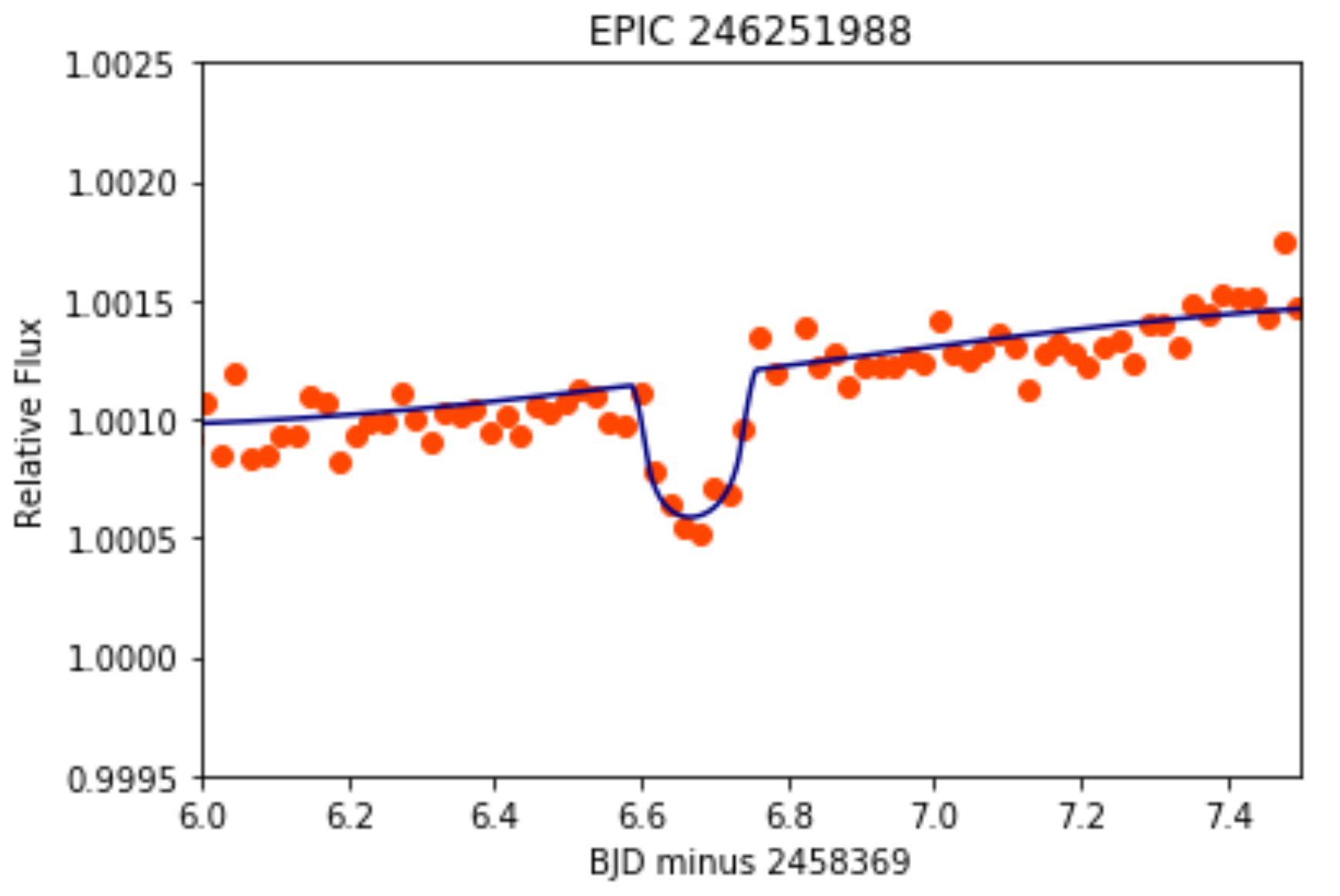
Planet Candidates in Campaign 19

In Kepler's second mission, K2, most sets of observations (called campaigns) provided 80-90 days of observations, but some, including Campaign 19, its final mission, were much shorter. Campaign 19 yielded only about 8 days of good data before Kepler ran out of fuel and the mission ended. Because of this, the planet transits that it was able to capture were mostly single transits. We have searched through the Campaign 19 dataset and visually identified single transit events around three stars: EPIC 246191231, EPIC 245978988, and EPIC 246251988.





Our team utilized the transit modeling program BATMAN (Kreidberg 2015) to fit transit curves to these data. Using the MCMC program emcee (Foreman-Mackey et al. 2013) in tandem with BATMAN, our team was able to create a likelihood function that modeled the light curve with four parameters for out-of-transit light curve variability and 6 parameters describing the shape of the transit: time of inferior conjunction, the natural log of the radius of the planet, impact parameter, transit duration, and quadratic limb darkening parameters.



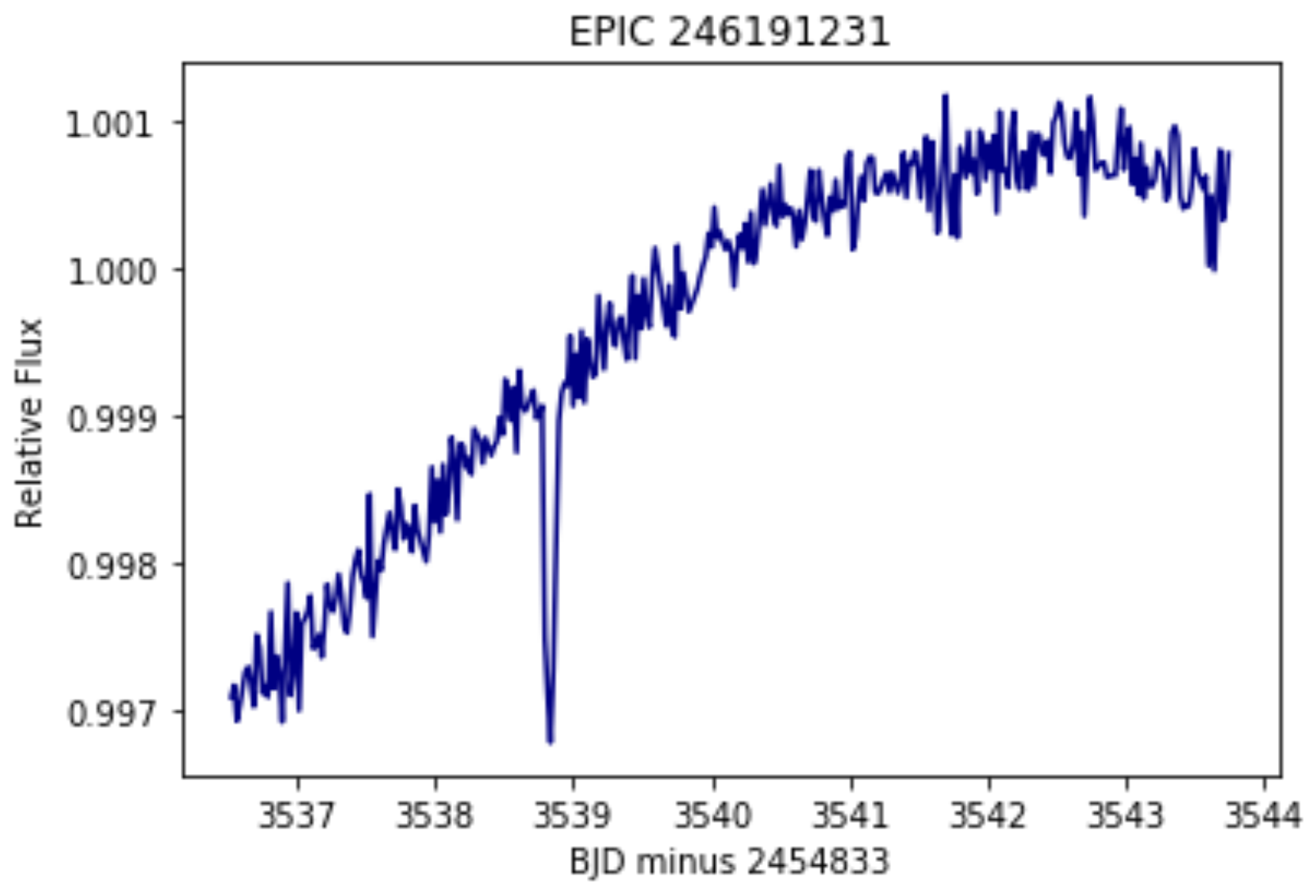
Our MCMC included a prior for the limb darkening parameters to ensure they agreed with stellar models. After running the MCMC chains with 40 walkers for 1,000,000 links, the best fit parameters yielded the transit fits shown above overlaid with the Campaign 19 data.

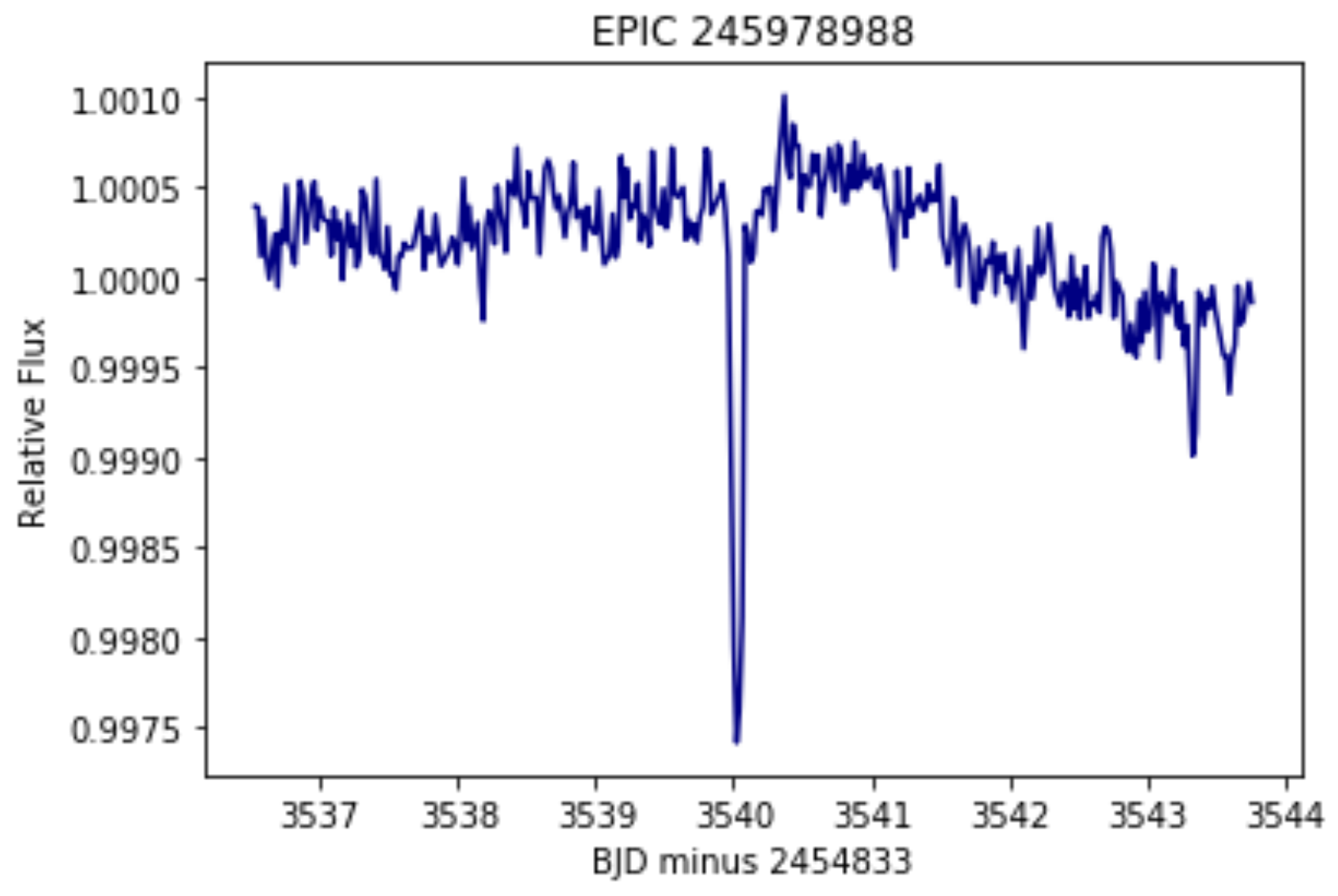
Table 1	EPIC 246191231	EPIC 245978988	EPIC 246251988
Time of Inferior Conjunction (BJD - 2454833)	$3538.8348^{+0.0041}_{-0.0052}$	$3540.0288^{+0.0030}_{-0.0059}$	$3542.6749^{+0.0036}_{-0.0038}$
Planet Radius (Star Radius)	$0.0444^{+0.0044}_{-0.0023}$	$0.0504^{+0.0035}_{-0.0022}$	$0.0218^{+0.0041}_{-0.0016}$
Planet Radius (Earth Radii)	$2.69^{+0.27}_{-0.14}$	$3.18^{+0.22}_{-0.14}$	$3.78^{+0.71}_{-0.28}$
Impact Parameter	$0.51^{+0.31}_{-0.34}$	$0.45^{+0.29}_{-0.30}$	$0.56^{+0.35}_{-0.38}$
Transit Duration (hours)	$2.62^{+0.27}_{-0.37}$	$2.45^{+0.32}_{-0.24}$	$3.34^{+0.40}_{-0.26}$
Quadratic Limb Darkening Parameters (u1, u2)	$(0.40 \pm .14, 0.35 \pm .15)$	$(0.43 \pm .14, 0.29 \pm .15)$	$(0.40 \pm .15, 0.34 \pm .15)$
Orbital Period (days)	$10.1^{+9.8}_{-3.5}$	$8.4^{+7.6}_{-3.0}$	$10.4^{+11.9}_{-2.8}$
Error of Each Light Curve Point	0.000178	0.000172	0.0000931

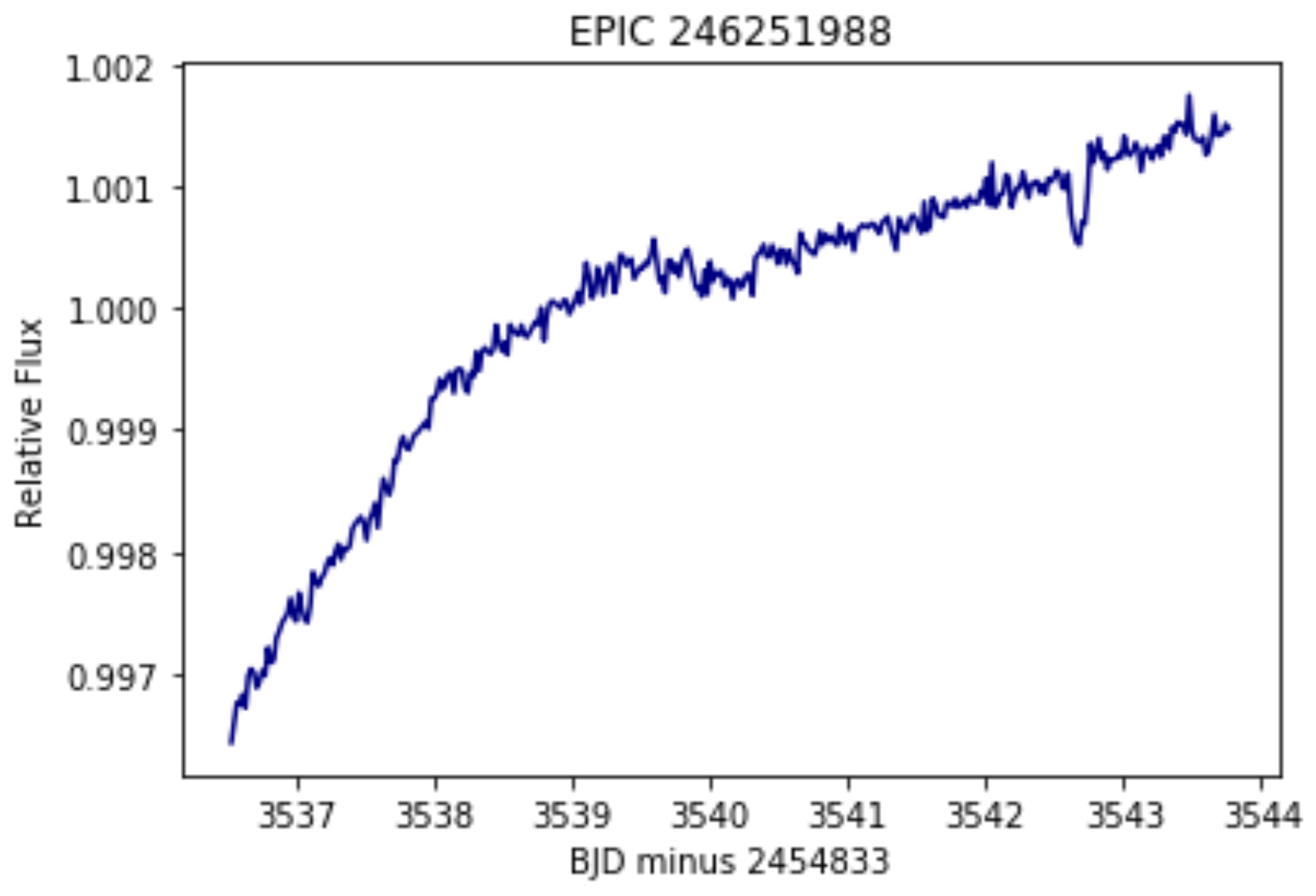
Like other programs, BATMAN fits for the radius of the orbiting planet in units of stellar radii. To determine the planets' radius in Earth radii, we multiplied each by its host star's radius. EPIC 246251988 is a G type dwarf, and so we were able to directly measure its spectroscopic parameters from a spectrum taken at Fred L. Whipple Observatory using the Stellar Parameter Classification software. Using these and the star's parallax and V-band magnitude, we were able to determine the star's fundamental stellar parameters using a calculator from da Silva et al. (2006). EPIC 246191231 and EPIC 245978988, however, are M type red dwarfs. It is more difficult to directly measure spectroscopic parameters for M-dwarfs from spectra, and so we utilized equations described in Mann et al. (2015) to determine each star's radius, mass, effective temperature, and luminosity.

Period Calculation from Single Transits

In order to determine the orbital period of each planet, our team used an orbital period equation described in Vanderburg et al. (2018). This equation utilizes Kepler's laws and the size of each star to determine how fast each planet is moving when it transits. That speed can be used to estimate the orbital period. The equation requires a known eccentricity and longitude of periastron, but as each of our systems have only a single transit and haven't yet been re-observed, we couldn't determine this value with any confidence. Instead, our team randomly generated 10,000 pairs of eccentricities and longitudes of periastron using ECCSAMPLES (Kipping 2014). We paired these with 10,000 randomly chosen samples from our MCMC to calculate an array of possible orbital periods for each of our systems.

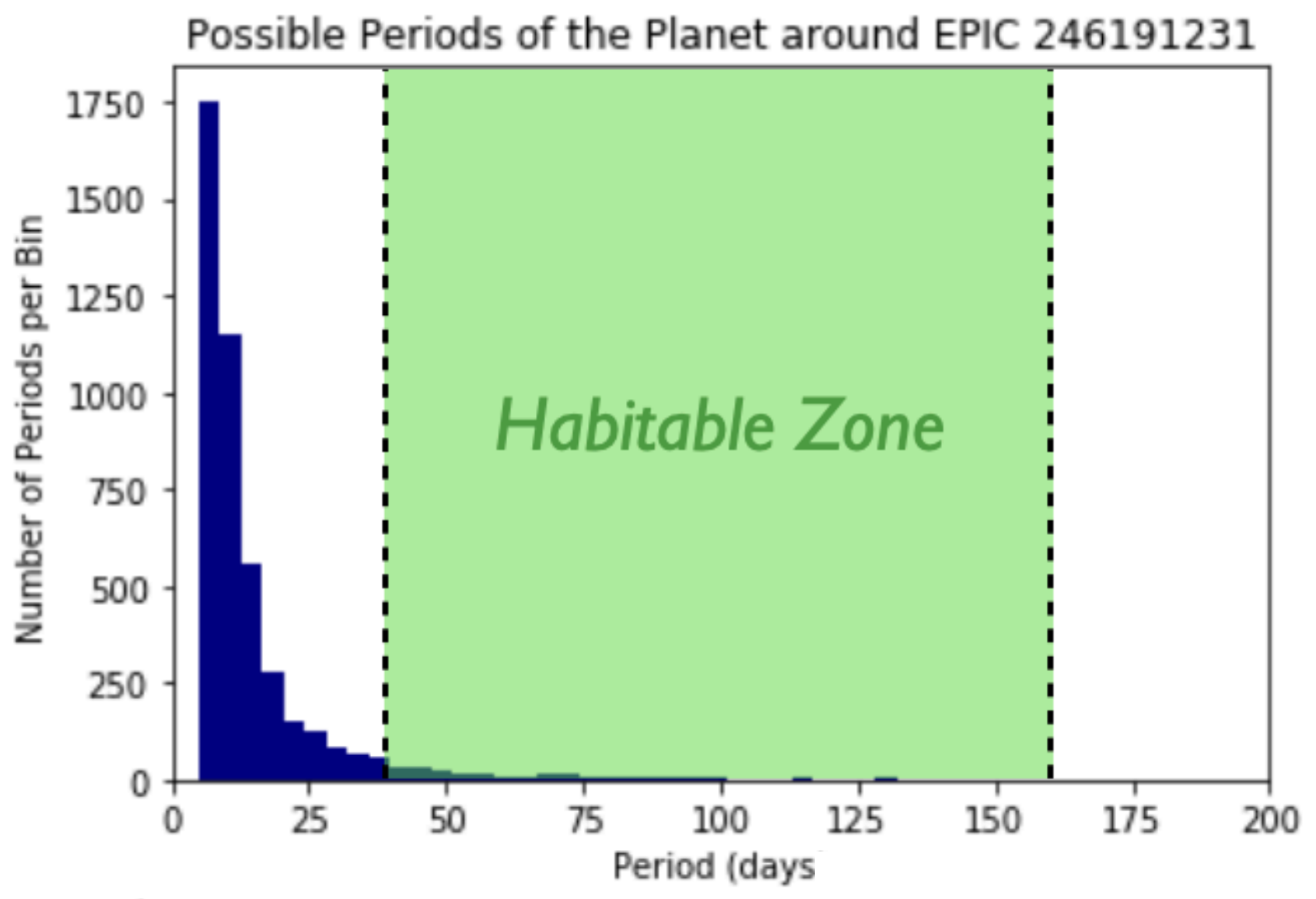


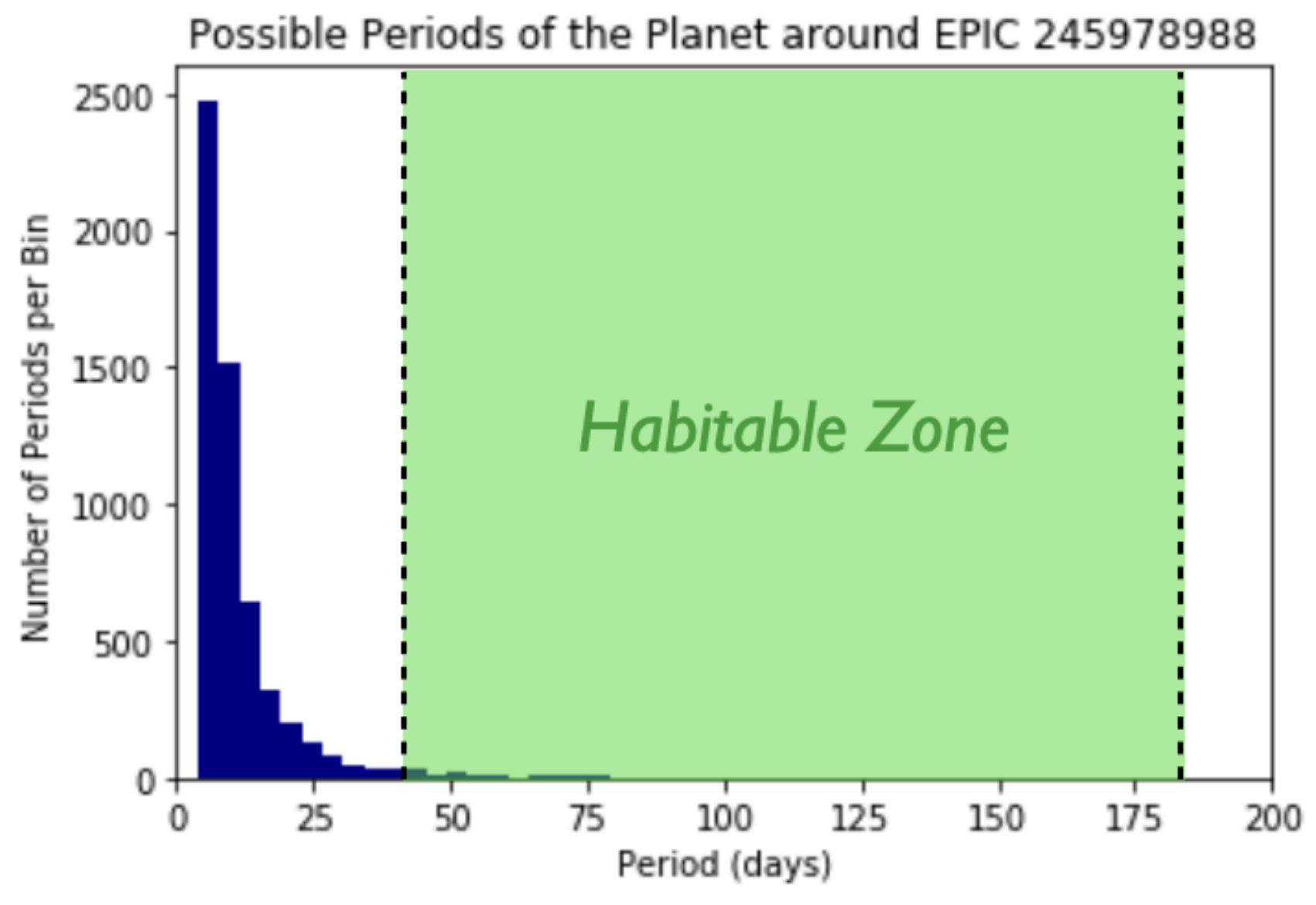


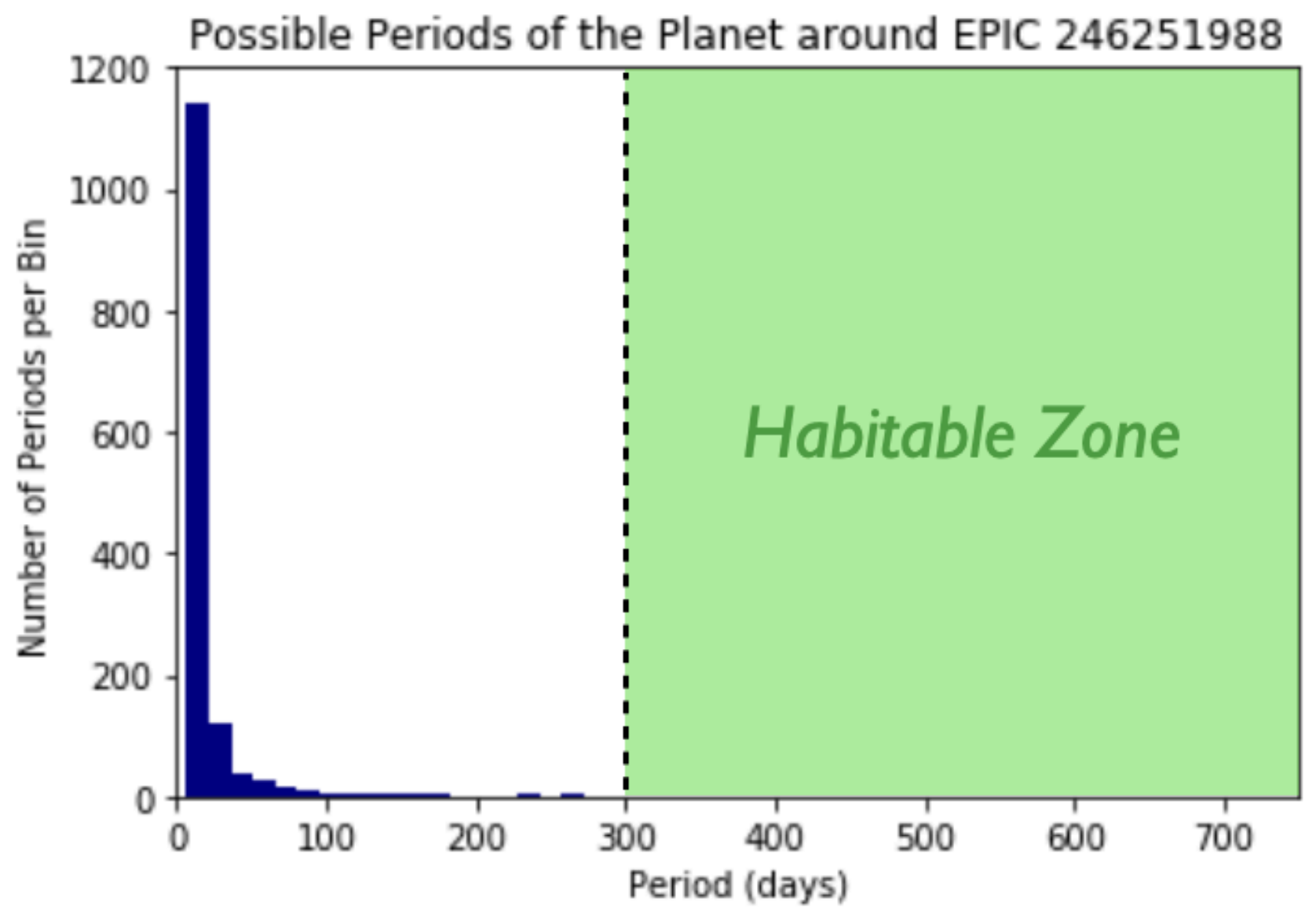


Our team placed a lower limit on the orbital periods according to longest uninterrupted section of the star's light curve. In the case of EPIC 246191231, for example, the lower limit placed on the orbital period was 5 days. EPIC 245978988 has a lower limit of 4 days, and EPIC 246251988 has a lower limit of 6.75 days. Because of the short observation time, we also rejected MCMC samples that corresponded to longer periods based on the probability of detecting a transit during the K2 observations.

Our team wanted to see whether these planets could be in the habitable zones of their stars. Using a calculator developed by Kopparapu et al. (2014), we were able to determine the habitable zones of each of our stars based on their luminosities and effective temperatures. For the two M-dwarfs, EPIC 246191231 and EPIC 245978988, these values were calculated from equations described in Mann et al. (2015). For EPIC 246251988, we were able to directly measure its effective temperature from its spectrum, while the stellar radius was calculated using a calculator from da Silva et al. (2006). The luminosity was calculated using the Stefan Boltzmann Law.







EPIC 246191231 has an optimistic habitable zone ranging from 40.5 days to 165.6 days. Of our calculated periods, 4.76% are in this range. EPIC 245978988's optimistic habitable zone ranges from 44.3 to 180.5 days, which encapsulates 1.89% of our possible periods. For EPIC 246251988, the habitable zone is farther out, ranging from 615.8 to 2230.4 days. Only 0.14% of our calculated periods fall in this range.

Each star's median period is listed in Table 1, along with other data.

Going forward, our team is working to incorporate radial velocity data and speckle images in our analysis to rule out massive stellar companions in these systems. We also were approved for TESS DDT observation of these systems. If we can capture more transits with TESS two minute cadence observations, we will be able to determine the period of the planets with high precision. These data will also help us validate our methods for analyzing single-transit planets. Using the TESS observations, we can compare the empirical period against our model's findings for the planets' periods, helping to determine the accuracy of our model. Our team expects to show with these observations how techniques developed with Kepler data can operate in tandem with TESS observations. These methods will also be useful going forwards to characterize the many single-transiting planets discovered by TESS.

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