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An Updated Ephemeris for K2-138 d

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Abstract

K2-138 d (EPIC 245950175 d) is one of five planets in a chain of 3:2 mean motion resonances discovered by Christiansen et al. in K2 Campaign 12. An additional planet, confirmed with the Spitzer Space Telescope by Hardegree-Ullman et al., is not in the resonant chain. The near first-order resonances, coupled with the planets being locked in a set of three-body Laplace resonances, make this system a unique target to study for transit timing variations (TTVs). As the predicted transit timing amplitude (~7 minutes) was below the typical transit timing uncertainty (~10 minutes) of the K2 data, Christiansen et al. were unable to detect TTVs for K2-138 d in the K2 time series. Here, we describe new observations that allow us to refine the ephemeris for K2-138 d and perform a brief search for TTVs. Our efforts result in a refined orbital period that is 19 times more precise than previously available measurements, but our data are insufficient to confirm a TTV signal for K2-138 d.

1. Analysis

K2-138 d was observed on 2019 August 31 (UT) and 2019 November 4 (UT) with the Wide-field Infrared Camera (WIRC) on the 200 inch Hale Telescope at Palomar Observatory, using the *J* filter on the aft filter wheel with the diffuser on the fore wheel, following the same setup as in Vissapragada et al. (2019). We obtained an additional 1.5 hr out of transit baseline before and after each transit, except on November 4, where we obtained 30 minutes post-transit. Light curves were also obtained from 10 comparison stars that fell within our field of view.

We use the `exoplanet` software package (Foreman-Mackey et al. 2021) to fit the target light curve, with normal priors on the ratio of semimajor axis to stellar radius, ratio of planet to stellar radius, impact parameter, orbital period, and stellar radius from Hardegree-Ullman et al. (2021). The timing is given a uniform prior, bounded at $\pm 3\sigma$ from the ephemeris in Hardegree-Ullman et al. (2021), and limb-darkening coefficients have been fixed to the values from Claret & Bloemen (2011). This methodology assumes the transit depth does not significantly change between the K2 and *J* bands because the transit depth uncertainty is large in a free retrieval, so the transit depths cannot be statistically differentiated from one another. The posteriors for both nights were then sampled with `pymc3`, following the methodology in Vissapragada et al. (2019).

From our analysis, we find that the transit midpoint for the August detection is $2458726.8223^{+0.0078}_{-0.0081}$ days (BJD–TDB). The above procedure was then repeated for the November detection, for which we find the transit midpoint to be $2458791.7629^{+0.0031}_{-0.0066}$ days (BJD–TDB).

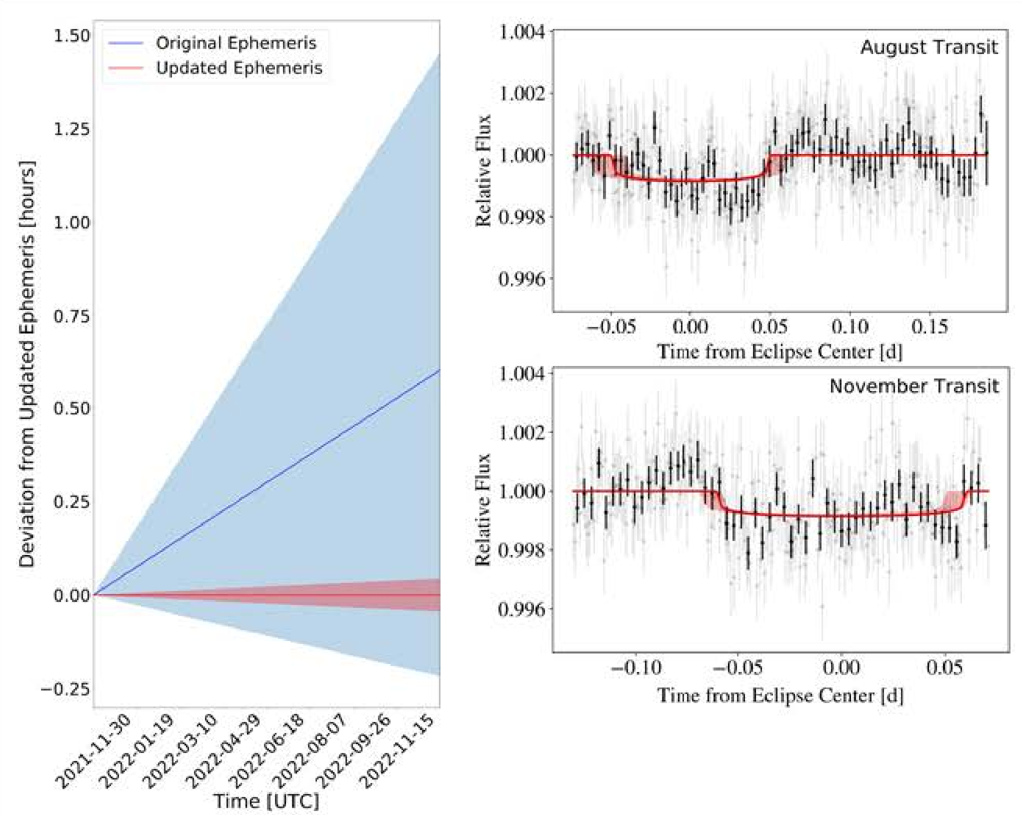

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Figure 1. Left: The difference between the original and updated ephemeris, starting from

the end of 2021 and propagated through to the end of 2022. The blue shaded region represents the uncertainty in the original ephemeris, while the red shaded region represents the standard deviation in the updated ephemeris. Upper right: The 2019 August transit. The red line represents our model fit with the shaded red being the 1σ confidence interval in the fit. Lower right: The 2019 November transit.

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These transit midpoint values are within the 1σ uncertainties of the Christiansen et al. (2018) ephemeris, and allow us to refine the uncertainties on the ephemeris considerably. To find an updated ephemeris, we performed a linear least squares fit to the observed transit midpoint values, weighted by the larger of either the upper or lower uncertainty of each transit midpoint value. This results in an updated ephemeris of:

$$E(\mathrm{BJD}) = (2458791.7629^{+0.0031}_{-0.0066}) + N \times (5.40511 \pm 0.00002). \qquad (1)$$

This new period is 0.49 minute longer than that of the original transit, with uncertainties 19 times more precise.

The new period can be used to search for transit timing variations (TTVs) in the two observations that were obtained. The observed transit time in August was 2458726.8223 days (BJD–TDB) and the calculated transit time was 2458726.8922 days. This corresponds to a difference of −100.7 minutes, indicating that the transit arrived 100 minutes earlier than expected. The observed transit time in November was 2458791.7629 days (BJD–TDB) and the calculated transit time was 2458791.7536 days, from which we find a difference of 13.3 minutes, indicating that the transit arrived 13 minutes later than expected. These calculations show large statistical deviations in the expected TTVs and are significantly larger than the predicted ~7 minutes timing variations. We attribute this discrepancy to significant correlated noise in the data and conclude that the noise prevents us from seeing the expected TTVs. We find uncertainties on the observed transit midpoint of ~11 minutes for K2-138 d (2MASS *J*-mag = 10.576), which is similar to uncertainties of ~11 minutes in the transit midpoint value for KOI-1783.01 (2MASS *J*-mag = 12.92) from Vissapragada et al. (2019). This indicates that the WIRC instrument at Palomar Observatory may be well suited for detecting timing variations on the order of tens of minutes, but will not constrain lower-amplitude TTVs.

These values represent a possible detection of TTVs for K2-138 d, but with only two observations and significant correlated noise in the data, we cannot claim a strong detection. The timing precision obtained from the WIRC observations is higher than for the K2 data, but insufficient to resolve the predicted amplitude of the TTV signal.

The K2-138 system represents a prime opportunity for additional observations to look for TTVs. Since Lopez et al. (2019) was able to characterize this system though radial velocity observations, detection of TTVs would provide a rare opportunity to characterize a system by using three different observational techniques. The ESA CHEOPS mission will be able to use this updated ephemeris to better locate and observe K2-138 d, hopefully leading to the detection of statistically significant TTVs and an enhanced understanding of this system.

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