Exoplanet Weather: Reassessing Time Variability in Exoplanet Phase Curves

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Research Goal

To identify whether time variability is present in the photometric phase curves of exoplanet HAT-P-7b, and if so, whether or not these variations are due to true atmospheric variations.

Introduction

Using detailed light curves from Kepler, we can construct a phase folded light curve (a phase curve) excluding the transit and the secondary eclipse, and study the way the exoplanet reflects the star's light during its orbit (for an overview, see Shporer, 2017). A study by Armstrong et al. (2016) claimed to find atmospheric variability on the planet HAT-P-7b using this method, and we attempted to confirm and extend their results.

Methods

→ Detrended the Kepler PDCSAP light curve of HAT-P-7, which includes the transit of HAT-P-7b, using a basis spline.

→ Split the light curve into 60 consecutive bins, phase-folding to create one phase curve per bin (illustrated in the figure below).

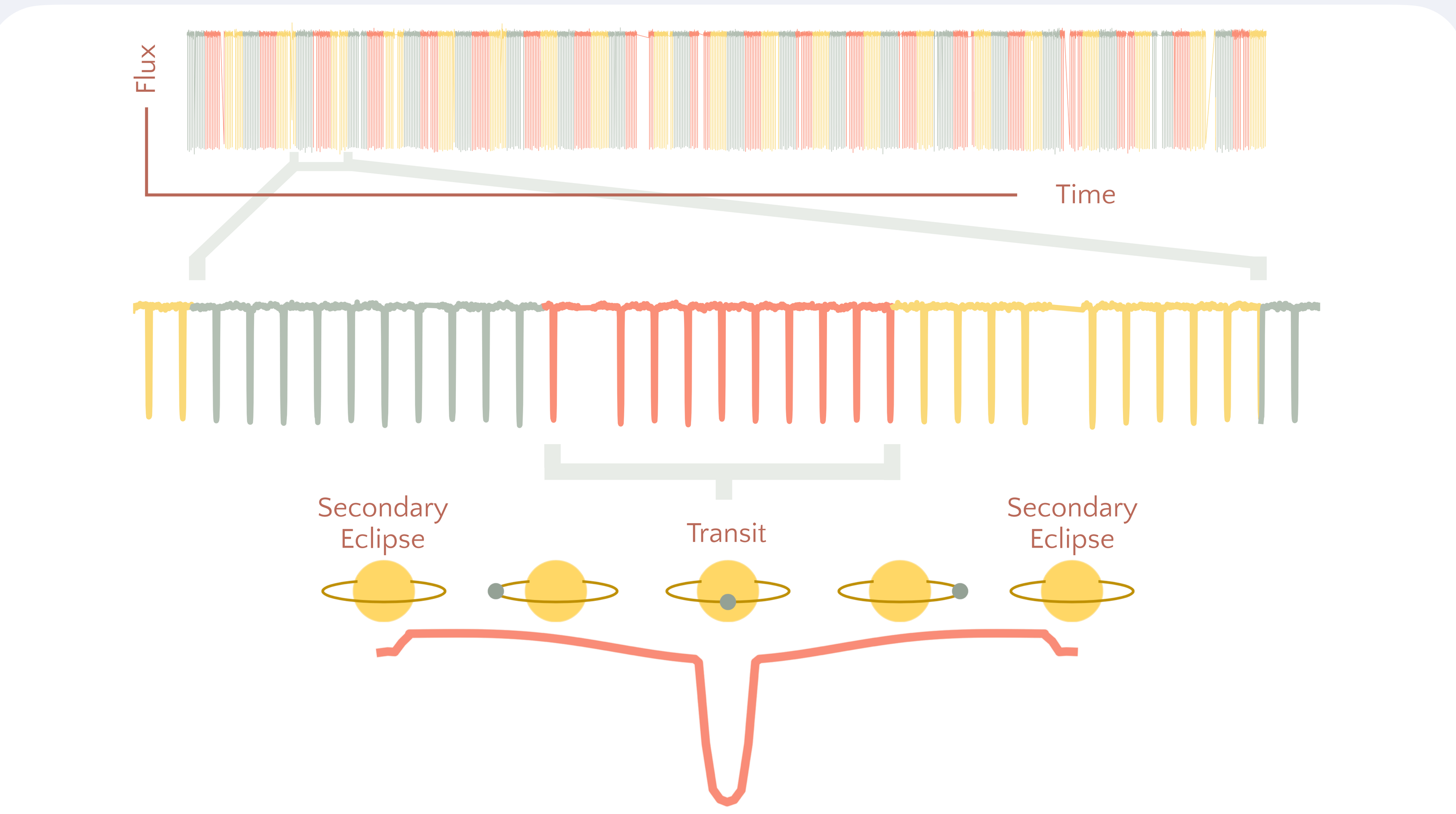

Figure 1: Top: The full Kepler light curve of HAT-P-7, split into 60 consecutive bins of 10 orbits of HAT-P-7b. Middle: Close-up view of about 70 days of Kepler data. Bottom: An example planetary phase curve including data from 10 consecutive orbits, along with a schematic of the relative position of the star and planet at several points in the orbit.

→ Removed the transit and secondary eclipse data.

→ Fit a three-harmonic sinusoidal model to each of the 60 consecutive phase curves using an MCMC algorithm (Foreman-Mackey et al., 2012).

→ Analyzed the time variation of phase offset and amplitude, quantifying the variation using a reduced χ^2 test.

→Tested the robustness and astrophysical significance of our result (described in Figures and Results).

Figures and Results

We measure the orbital phase of maximum brightness (otherwise referred to as "phase" or "phase shift/offset") in each of the 60 consecutive phase curves, and **we see results similar to those of Armstrong et al.**

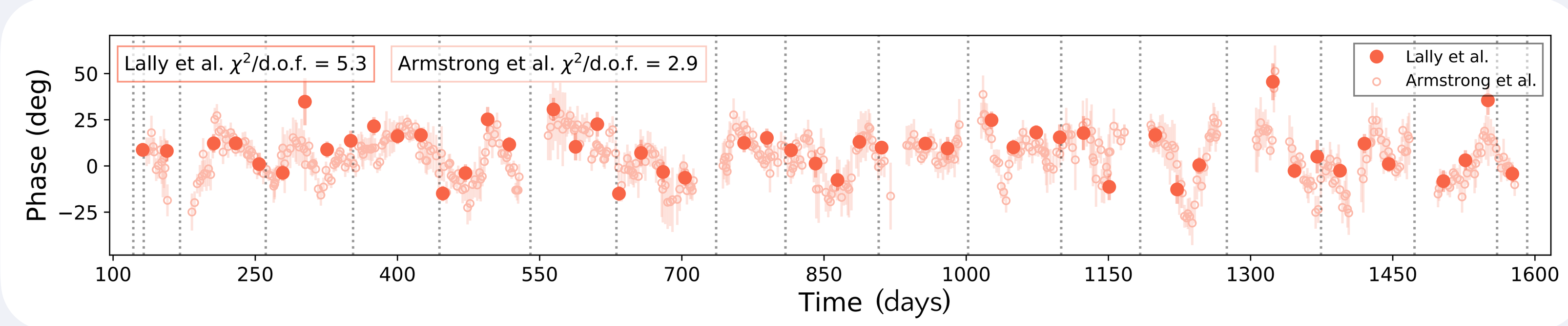

Figure 2: Measurements of the phase offset of HAT-P-7b's phase curve over time. Our measurements are shown in bold points, plotted with the phase offsets from Armstrong et al. (2016) shown in open points. The Armstrong et al. result shows ~10x more points, due to their use of a sliding bin of 10 orbits, oversampling the Kepler data by a factor of 10. The vertical dotted lines show where the Kepler light curve is broken into quarters. The χ/d.o.f. value is shown for each result. Though our result appears to show significant atmospheric variability similar to that identified by Armstrong et al., the identified variations may be due to factors other than atmospheric variations on HAT-P-7b.

In order to test whether the identified variations are due to real atmospheric effects or some other factor, we inject a static phase curve signal into the light curves of several stars similar to HAT-P-7 in effective temperature, radius, brightness, and observing baseline. We then repeat our analysis methods to recover phase offsets from the injected phase curves. **We find that we also recover apparently significant phase offset variations from these injected phase curves which are known to be static.**

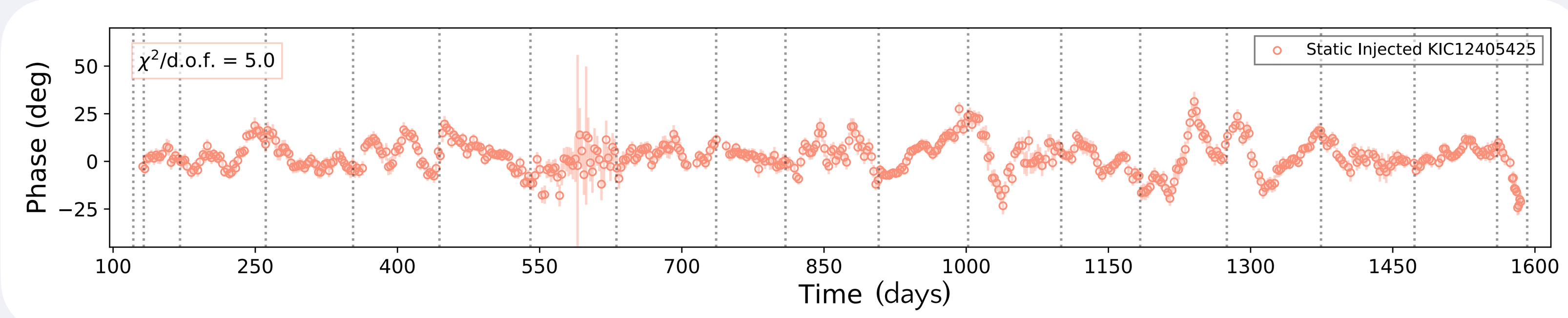

Figure 3: Measurements of the phase offset recovered from static phase curves injected into KIC 12405425. The vertical dotted lines show where the Kepler light curve is broken into quarters, and the Y axis is on the same scale as the phase plot in Figure 2 to aid by-eye comparison. The χ/d.o.f. value is shown in the top left. By applying our analysis methods to a light curve with static injected phase curves, we recovered "variations" that are comparable (both qualitatively, and based on the χ/d.o.f.) to what we identified for HAT-P-7b.

If phase offset variations are due to real variations in the atmosphere of HAT-P-7b, they should manifest in short lightcurve segments at the period of the planet. Periodograms of sections of the Kepler short cadence lightcurve of HAT-P-7, with the average planet signal over the full lightcurve removed, show that significant periodic variations are not centered at the orbital period of HAT-P-7b. **This suggests that the detected variations are not necessarily from changes in the planet's atmosphere**, and may instead be due to periodic variations in the host star.

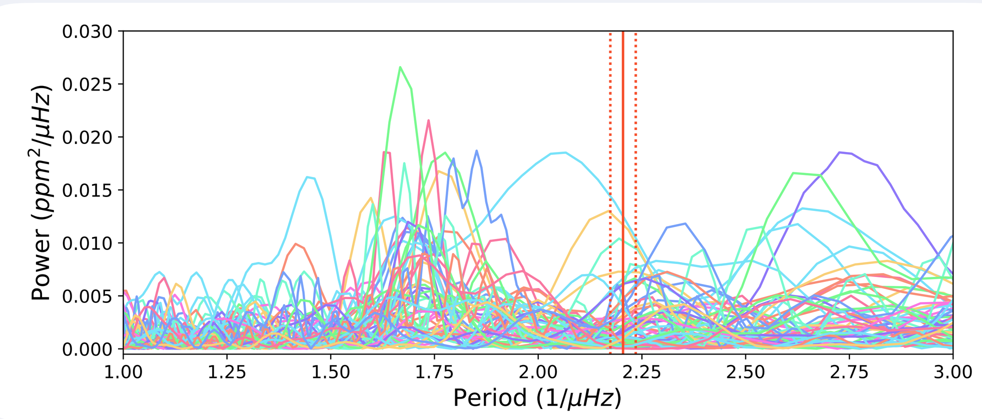

Figure 4: Periodograms of 60 segments of the short-cadence Kepler lightcurve of HAT-P-7 with the average planet transit signal removed. A vertical line is shown at the period of HAT-P-7b, and dotted vertical lines are shown at the range of periods where we would expect to see planetary signals. The periodograms do not display any significant peak at or near the planet's period, suggesting that any detected periodic variations may be due to sources other than the planet.

Conclusion

Although we measured similar phase variations in HAT-P-7b as those reported by Armstrong et al., we do not necessarily confirm that these variations are caused by real atmospheric changes on the exoplanet. Based on the injection/recovery tests and Fourier analysis, it seems that at least some of the variations detected may be due to variations from sources other than the planet itself, potentially including the host star.

Going forward, we suggest using injection/recovery tests to probe the significance of future detections of exoplanet atmospheric variability. Finding stars for injection would be straightforward for wide-field optical surveys such as Kepler and TESS, where many stars are observed simultaneously. We can also expect stellar variability to be lower-amplitude in TESS lightcurves compared to this Kepler dataset, since TESS observes in a redder bandpass. However, TESS observations will not be as precise as this dataset, nor will the observing baseline be as long. With four years of extremely precise photometry, the Kepler dataset on HAT-P-7 is one of the highest-quality photometric time series in existence, and may remain so for some time.

This result underscores the extreme difficulty of robustly measuring photometric variability in the atmospheres of exoplanets, and suggests that future observers will need to consider the host star's variability before characterizing the variability of the planet's atmosphere.

Acknowledgements

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Foreman-Mackey, D. et al. P.A.S.P. 125, 306, (2012).

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