

Exoplanet WASP-76 b secondary eclipse timing deviation possibly indicating the existence of additional unseen components

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Abstract. The work involves the homogeneous processing of observations of 10 exoplanets, each with at least four secondary eclipses, using data from the Spitzer/IRAC space telescope in the $3.6\ \mu\text{m}$ band. The aim is to search for infrared brightness profile asymmetry on the surface of these exoplanets. To achieve this, the model parameters were estimated using the maximum likelihood method, incorporating correlated noise modeled as a stationary Gaussian process. The effect of intrapixel sensitivity variations is modeled using a 2D Fourier series. For WASP-76 b, a statistically significant shift of secondary eclipse center of -2.42 ± 0.57 min was detected. This shift possibly indicates the presence of additional invisible components in the planetary system.

Introduction

Observations in the infrared spectrum allow us to detect not only transits, but also secondary eclipses (when the planet sets behind the star). These observations enable us to determine the orbit of the planet and its average temperature, but in this study, we were interested in more refined effects, specifically, irregularities in the shape of the light curve at the beginning and end of the eclipse, which could be caused by variations in brightness across the planetary surface.

The most suitable candidates for observing the effect in question are hot jupiters. These planets have the highest temperatures and radii, and as a consequence, the deepest secondary eclipses. Furthermore, these types of planets should be tidally locked to their host star, allowing for the observation of stationary current patterns from the heated dayside to the nightside. At the same time, the hottest region should shift in relation to the substellar point, making it easier to detect the uneven surface brightness effect.

In this study, we analyzed the observational data from secondary eclipses of ten exoplanets located close to their host stars (hot jupiters, hot neptun, and super-earth), which were obtained using the IRAC instrument on the Spitzer Space Telescope. This work builds on previous research [1].

Several articles by other researchers have addressed a similar research topic. Specifically, in [2, 3, 4], images of the surface of HD 189733b were obtained. The unique aspect of this study is that data from ten exoplanets was analyzed simultaneously in order to identify the characteristic features of their light curves. Additionally, a different IRAC bandpass was used, $3.6\ \mu\text{m}$ instead of $8\ \mu\text{m}$.

The choice of this spectral range was due to its previous use in the aforementioned study [1]. Although the eclipse depth in this range is less than that observed at $8\ \mu\text{m}$, it does not allow for direct recording of surface brightness inhomogeneities. Transitioning to the $8\ \mu\text{m}$ range would necessitate revising the noise model, which is noticeably distinct from those employed in previous studies, according to [5].

The aim of this study is to analyze several exoplanets simultaneously in order to identify the distinctive features of their light curves.

1. Methodology

During the course of the work, observations were analyzed for 10 exoplanets: HD 209458 b, HD 189733 b, GJ 3470 b, WASP-12 b, WASP-43 b, WASP-76 b, HAT-P-2 b, 55 CANCRI e, WASP-80 b, and WASP-52 b.

The complete photometry algorithm has been previously presented [1]. A distinctive aspect of this study is a more thorough consideration of outliers in the data, and the fact that for several objects, frames containing only one or two outliers were not excluded from analysis, as otherwise a significant portion of the observational data would have been disregarded.

To account for strong correlated noise, a maximum likelihood method was employed, with the correlated noise being represented as a stationary Gaussian process.

In this study, a uniformly bright disk model was employed as a representation of the signal from the target object (the most basic light curve from the article [6]). As the aim of the research was not to simulate the heterogeneity of surface brightness, but rather to identify discrepancies with the simplest model, this model included two primary free parameters that did not account for noise: the relative brightness of the planet compared to the star and a time offset for the center of secondary eclipse relative to the model-predicted orbital position. For most targets, the assumed orbit was circular, with the notable exception of exoplanet HAT-P-2b, which exhibits a significant level of eccentricity.

The modeling of the noise component involved a modification of the approach proposed in [1]. Specifically, the part responsible for uneven pixel sensitivity included a variable number of coefficients rather than the fixed 20 previously used.

The number of coefficients was selected individually for each pixel in each object and ranged from 4 to 68. This decision was based on the statistical significance of model improvement, with the choice of number of coefficients determined by when the significance reached a level of 2 standard deviations.

Conclusion

As a result, the following eclipse parameters were obtained (see Table 1). It should be noted that for all planets, the data are presented as deviations from a circular orbit, except for HAT-P-2 b, where the result is compared to a highly elongated orbit ($e = 0.50833, \omega = 186.96^\circ$). The offset in the eclipse timing for each exoplanet can be explained by two factors: the heterogeneity in surface brightness and the non-zero orbital eccentricity.

Object	Center offset (min.)	(rad. of the planet)
HD 209458 b	-0.38 ± 0.64	-0.036 ± 0.057
HD 189733 b	0.18 ± 0.39	0.021 ± 0.044
GJ 3470 b	33.22 ± 8.4	9.32 ± 2.35
WASP-12 b	0.33 ± 0.98	0.033 ± 0.098
WASP-43 b	-0.37 ± 0.45	-0.063 ± 0.076
WASP-76 b	-2.42 ± 0.57	-0.217 ± 0.051
HAT-P-2 b	0.30 ± 1.47	0.039 ± 0.193
55 CANCRI e	3.00 ± 1.53	3.428 ± 1.755
WASP-80 b	-1.18 ± 1.72	-0.126 ± 0.184
WASP-52 b	0.02 ± 1.77	0.003 ± 0.198
weighted average score	-0.10 ± 0.25	-0.010 ± 0.029
Object	$e \cos(\omega) (\times 10^{-3})$	Depth of eclipse (ppm)
HD 209458 b	-0.13 ± 0.20	1205 ± 43
HD 189733 b	0.09 ± 0.19	1470 ± 38
GJ 3470 b	10.86 ± 2.74	48 ± 50
WASP-12 b	0.33 ± 0.98	3461 ± 194
WASP-43 b	-0.50 ± 0.60	3211 ± 108
WASP-76 b	-1.46 ± 0.34	2755 ± 92
HAT-P-2 b	—	916 ± 97
55 CANCRI e	4.44 ± 2.27	101 ± 69
WASP-80 b	-0.42 ± 0.61	959 ± 123
WASP-52 b	0.01 ± 1.11	2010 ± 171

TABLE 1. Model parameters

It is worth noting the data obtained for exoplanets GJ 3470 b and 55 CANCRI e, the eclipses of which are recorded with a significant error. In particular, GJ 3470 b. It is also significant that the offset of the eclipse centre varies greatly

depending on the model used, which could indicate that there is no eclipse as such in the observational data and the recorded effect is a measurement error.

For most objects, there is no statistically significant offset in the center of secondary eclipses. However, there are two exceptions: 55 Cancri e, which is part of a multi-planet system, and WASP-76 b. In the case of 55 Cancri e, the planet may have a non-zero eccentricity, while in the case of WASP-76 b, it looks unlikely. This object also show an earlier occurrence of the eclipse than would be expected from a non-uniform brightness, despite the absence of any other exoplanets in the system. It is worth noting that the second star in this system is located at a distance of 53.0 ± 8.8 AU from the main star, and the expected period of the system is approximately 300 years. This should not significantly affect the timing of eclipses observed over the two-year period covered by the Spitzer Space Telescope.

References

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