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Detectability of tidal deformation in close-in exoplanets

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Abstract

Close-in planets are influenced by the extreme tidal forces of their parent stars. These forces deform the planets causing them to attain nonspherical shapes. The nonspherical shapes, which we model as triaxial ellipsoids, can impact the observed transit lightcurves and the parameters derived for these planets. We modify a transit analysis tool to investigate the instrumental precision required to detect tidal deformation in these planets. The transit model is parameterized by the second fluid Love number thereby allowing us to derive an estimate of the Love number that best matches the observations. By simulating the interesting cases of WASP-103b and WASP-121b, we find that an instrumental precision of better than 50 ppm/min is required to reliably estimate the Love number and detect tidal deformation. Attaining this precision level will require several observations of the planet's transit.

1. Introduction

Planets reach their final shapes having attained hydrostatic equilibrium from balancing gravitational, pressure, and other external forces acting on them. Planet shapes are often assumed to be spherical for simplicity but they are triaxial in reality. For very-short-period planets (P < $1-2$ days), the close proximity to their stars exposes them to strong tidal forces which deforms them and increases the triaxiality of their equilibrium shapes. Tidal deformation is particularly significant for planets orbiting close to their stellar Roche limits and a number of planets have been discovered to orbit so close to this limit that they are bordering on tidal disruption [2].

1.1. Modeling transit of deformed planets

We model the shape of a deformed planet by a triaxial ellipsoid (with axes a, b, c) following the analytical model from [1]. The deformation to the planet is described using a Love number approach such that the fluid second Love number for radial displacement (h_f) is related to the radial deformation of the planet. h_f is a dimensionless quantity that quantifies the deformation to a planet due to a perturbing potential. The magnitude of h_f depends on the mass distribution of the planet and thus provides information about the interior structure of the planet. More homogeneous planets have higher h_f whereas planets that are more centrally condensed have lower h_f. The physical values of h_f range from 1 to 2.5 with the maximum value being for an incompressible homogeneous planet.

A tidally locked planet will have a circularized orbit and also synchronous rotation so that the semi-principal axis a of the planet always points towards the star. This leads to a deformation along a and the planet shape is such that $a > b > c$. We define a volumetric radius for the ellipsoid so that $R_v = (abc)^{1/3}$

Our deformed planet light curve model allows the projection of the ellipsoid and generation of the corresponding transitlight curve. The projected shape of the ellipsoid on the stellar disk is an ellipse whose dimensions depend on the phase of the planet due to rotation of the ellipsoid with phase.

2. Transit signature of deformation

The observable signature of planet deformation is the residual between the light curve of the deformed planet and the best-fit spherical model. To show this, we simulated the light curve of WASP-103b (22.2 hr period) as a deformed planet and perform a least square fit using a spherical planet model. The signature and amplitude of deformation is seen in the residual of the fit in Fig.1. The parameters derived from the fitting process

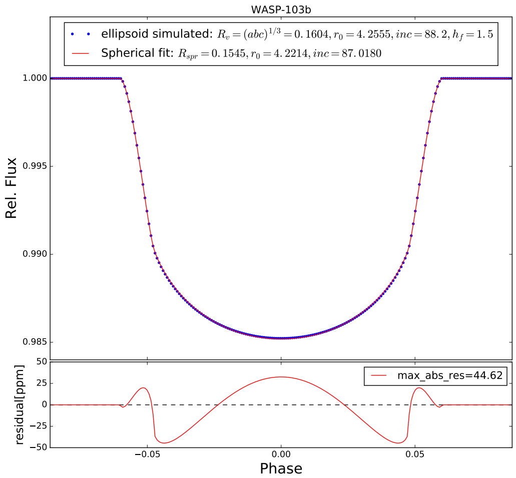

Figure 1: Signature of deformation from spherical fit to simulated deformed WASP-103b light curve.

are systematically incorrect as they adjust in attempt to mimic the signature of deformation. The signature of deformation manifests in two regions, first at ingress and egress phases owing to oblateness ($b > c$) of the planet. A second prominent feature from tidal deformation is seen as a bump centered on the mid-transit phase due to the varying star eclipsed area caused by ellipsoid rotation as it transits.

3. Detectability of deformation and measurement of Love number

To correctly estimate the planet transit parameters from the light curve, our ellipsoidal model can be used to fit the transit observation. In doing so, we also obtain a value for the Love number that best fits the observation if there is enough precision in the data. Detectability of tidal deformation using the ellipsoidal model relies on the ability to recover a nonzero value of h_f that satifies $h_f \geq 1$ with statistical significance from the fitting process.

Figure 2 shows the detectability plot with results for different noise levels added to the observation. We see that the significance of h_f detection above 1 reduces as the noise level of the observation increases. For instance, at 50 ppm noise level, h_f samples are well above zero, implying that the ellipsoidal model provides a better fit than the spherical model. Beyond 50 ppm, fitting the observation with a spherical model becomes increasingly more probable and we cannot distinguish between a spherical and oblate planet.

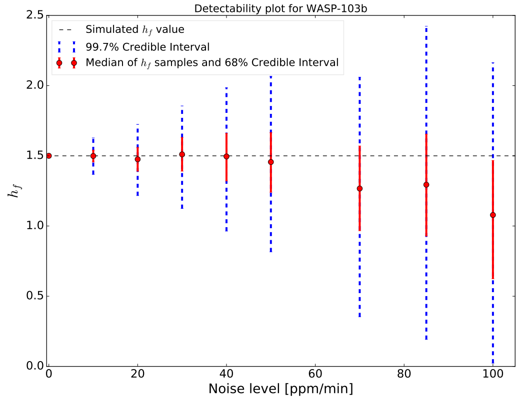

Figure 2: Detectability of deformation in WASP-103b considering different noise levels. The black dashed line is the simulated h_f value. The points are the medians of the h_f samples at each noise level. The red and blue error bars show $\pm 1\sigma$ and $\pm 3\sigma$ credible intervals

4. Summary and Conclusions

Our work showed that the instrumental precision needed to detect tidal deformation is ≤ 50 ppm which can be attained by the upcoming CHEOPS instrument with $\sim$ 300 transits for WASP-103b and 40 transits for WASP-121b. The HST can also attain this precision for WASP-103b in approximately 40 transit observations. Fewer transit observations will however be required if such short-period planets are found transiting very bright stars. However detection can still be severely hampered by improper modeling of the limb darkening which, in some cases, can cause the signature of deformation to be subdued, leading us to infer sphericity from the observations.

Acknowledgements

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