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Determining exoplanet cloud properties using optical phase curves

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Abstract

Accurate photometry of spatially unresolved exoplanet+star systems is setting key constraints on various aspects of close-in exoplanet atmospheres (geometric albedos, peak brightness offsets, temperatures, occurrence of clouds and haze, etc.) through the investigation of the planetary phase curves [1, 2, 3]. Such work has been enabled by observations of the optical phase curves of hot Jupiters by COROT and Kepler. A theoretical framework to investigate such phase curves and recover the information contained in them has been missing, however. We have set out to establish such a framework, which allows us to connect fundamental properties of the exoplanet atmosphere (cloud spatial distribution, optical depth, cloud particle scattering properties) to the observable phase curves.

1. Methodology

Our framework (García Muñoz & Isaak, *submitted*) relies on a recently devised Pre-conditioned Backward Monte Carlo (PBMC) algorithm [4] that computes the phase curves of inhomogeneous planets without any computational overhead with respect to the solution of homogeneous planets [5, 6]. The calculation proceeds by simulating a number of one-photon numerical experiments. Since it is a backward algorithm, each experiment traces the trajectory of a photon from the observer through the scattering atmosphere. The contribution to the estimated radiation at the observer's location is built up by adding the contributions every time the photon undergoes a collision. The simulation is terminated when the photon is completely absorbed in the atmosphere.

The algorithm includes a scheme to select the photon entry point into the atmosphere based on the local projected area of the 'visible' planet disk. This strategy ensures that all simulated photons contribute to the estimated radiation at the observer's location.

The output of each simulation is the planet-to-star brightness ratio for reflected starlight:

$$F_p/F_\star = (R_p/a)^2 A_g \Phi(\alpha) \quad (1)$$

where R_p and a are the planet's radius and orbital distance, respectively; A_g is the geometric albedo and $\Phi(\alpha)$ is the planet phase function. By sampling the star-planet-observer phase angle α, we build the synthetic model phase curves that allow us to compare with available exoplanet phase curves.

2. Investigation of cloud properties

In the contribution, we present our framework and use the test case hot Jupiter Kepler 7b to illustrate the cloud properties that can be constrained from optical phase curve measurements, as well as possible degeneracies between key atmospheric parameters. Further, we discuss our findings in the context of upcoming space missions and General Circulation Models.

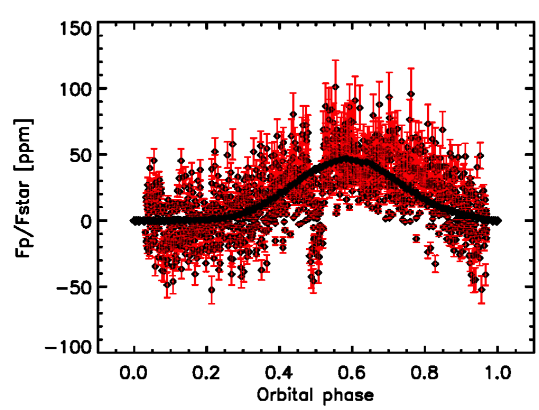

Figure 1: Observed (black diamonds+red bars) and modeled (black symbol) phase curve of Kepler-7b. Measurements are from Ref. [3]. Model fitting of the observations enables us to investigate the information content of the measured phase curve.

3. Outlook

Within coming years, first CHEOPS and TESS and then PLATO will greatly increase the number of available exoplanet phase curves, thus allowing for comparative studies. The devised methodology paves the way for the investigation of exoplanet cloud properties with data to be obtained by these missions. Atmospheric studies of exoplanets with optical phase curves will primarily focus on hot Jupiters, although Neptune-sized planets may also be amenable to such studies.

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