
# Virtual Research Presentation Conference

## Forward modeling and retrieval framework in the UV-NIR for directly imaged exoplanets bearing cloudy atmospheres

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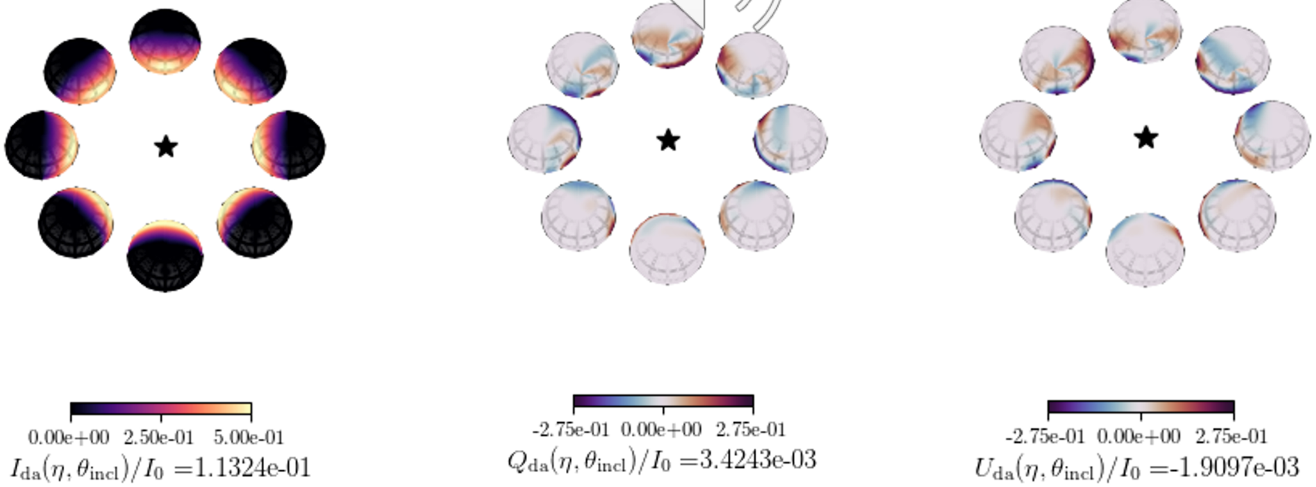
# Tutorial Introduction

**Abstract**: We have carried out an expansion of our semi-analytic 3D radiative transfer modeling framework for brown dwarfs to include stellar light reflected by exoplanets with cloudy atmospheres. Using Mie theory to compute scattering by cloud and haze consisting of spherical particles, we show that the currently widespread use of the Henyey-Greenstein Rayleigh composite approximation results in a blurring of the phase-dependent features of exoplanet lightcurves, causing a 14-40% loss of parametric sensitivity in an average measurement for SNRs between 5-500. The approximation creates the misleading impression that clouds are as polarizing as Rayleigh scatterers, regardless of their droplet size. This results in a negligible sensitivity of HGR simulations to polarization measurements at the SNRs considered, whereas Mie simulations show a 10-30% gain in parametric sensitivity through the addition of polarimetry.



# Problem Description

a) Context: The characterization of exoplanet atmospheres requires observation techniques like transit spectroscopy or direct imaging. Transit spectroscopy is applicable to planets that eclipse their stars, reducing their subset to close-in orbits that are edge-on viewing geometries. Direct imaging (Malbet et al. 1995; Angel and Burrows 1995), on the other hand, allows the study of planetary atmospheres for a wider range of planetary and orbital radii and orientations. It is, however, limited by the diffraction limit of the instrument to planets with sufficient angular separation from their host star, and requires a minimum flux ratio between the planet and the star. As a result, direct imaging observations by JWST will be restricted to self-luminous, wide-orbit gas giant exoplanets and BDs. These objects require accurate radiative transfer modeling of their thermal emissions (Sengupta and Marley 2009; Marley and Sengupta 2010; Stolker et al. 2017; Sanghavi and Shporer 2018; Sanghavi and West 2019) for the scientific interpretation of their observations.

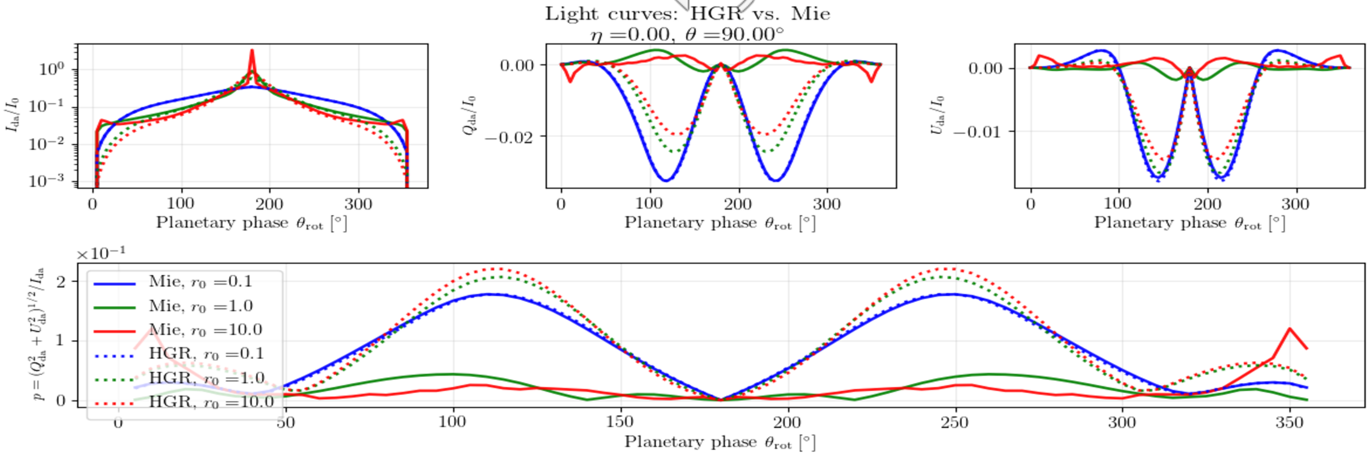
b) SOA: We have extended the work of Sanghavi and Shporer (2018) and Sanghavi and West (2019) to include starlight reflected in the UV-Vis-NIR by cloudy exoplanet atmospheres. This modeling capability is needed to simulate future NGRST, HabEx, and LUVOIR measurements. Each of these missions will carry out direct imaging studies of exoplanets in the UV-Vis-NIR. These observations take the form of photometric lightcurves, and spectra, with eventual polarimetric synergies from instruments like GPI (Macintosh et al. (2008)) or SPHERE (Beuzit et al. 2008). Our semi-analytic framework retains the 1D analytic RTM vSmartMOM (Sanghavi et al. 2014) as the core solver, allowing a fast and accurate, full microphysical representation of scattering by spherical haze/cloud particles using Mie theory (Sanghavi 2014; Sanghavi and Stephens 2015). Our work offers an analytic alternative to Monte Carlo and single-scattering ray tracing approaches that have be used for hitherto simulations of exoplanet lightcurves (Ford et al. 2001; Dyudina et al. 2005; Tinetti et al. 2006) by extending the radiative transfer modeling of exoplanets to multiple-scattering, multilayer analytic simulations with realistic phase matrices to represent scattering and polarization by haze and cloud particles instead of the commonly used Henyey-Greenstein approximations.

c) Relevance to NASA and JPL: JPL is a leading technology contributor to JWST, NGRST, HabEx, and LUVOIR, which will successively be able to directly image exoplanets in the near-, mid- and long-term. NGRST, HabEx and LUVOIR will use incremental coronagraphic improvements combined with star-shade technologies to successively reduce the the angular separation of planets from their host stars to eventually allow the direct imaging of Earth-like orbits and habitable worlds. Our modeling capability will enable the exoplanet research and instrument development community to carry out critical synthetic sensitivity studies to gauge the pre-launch performance of the instrument, as well as to meaningfully interpret direct imaging observations after launch.

# Methodology

a) Formulation, theory or experiment description: We use simulations employing Mie theory to show the errors incurred in the computation of light curves for cloud/haze particles of different sizes by the use of composite Henyey-Greenstein and Rayleigh (HGR) approximations. We subsequently set up a simple experiment to simulate synthetic photometric lightcurves, and carry out principal component analysis (PCA) on a sample set of lightcurves obtained for four variable parameters, viz., cloud grain size, chemical composition, inclination angle and planetary oblateness to compare our ability to simulate the observed degrees of freedom in measurements under different noise conditions through the use of the composite HGR approximation and Mie Theory.

b) Innovation, advancement: Our side-by-side comparisons show that HGR approximations blur the angular information contained in the lightcurves for all cases barring that of the smallest scattering particles. HGR approximations mislead us to expect greater degrees of polarization by larger sized scattering particles, when they actually exhibit a strongly depolarizing behavior.

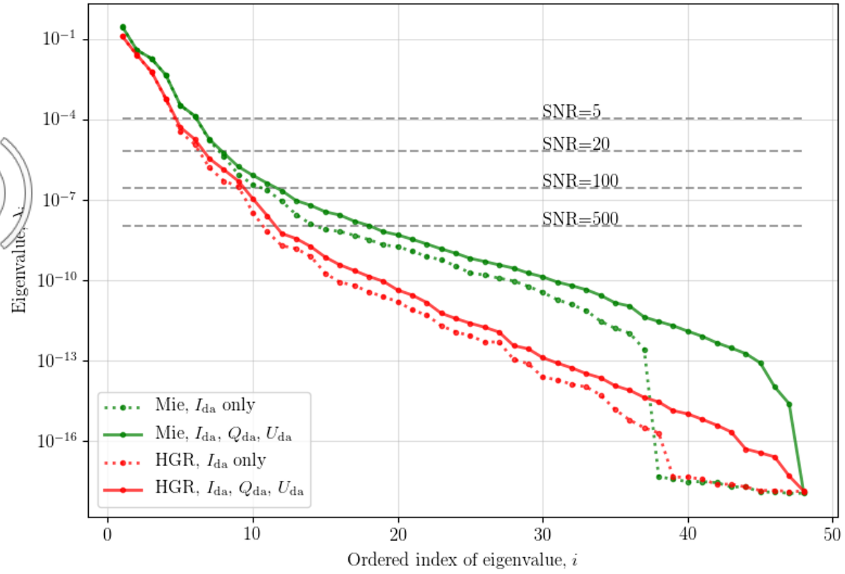


# Results

a) **Accomplishments versus goals:** Our research goal was to understand the information contained in observations of reflected light, and the amount of the information that could be extracted by different modeling approaches (mainly Mie vs. HGR). We were able to show this using PCA for different instrumental SNRs.

b) **Significance:** Our study (Sanghavi et al. 2020 (under revision)) re s that polarization measurements add substantial parametric information instrumental SNR>20 when Mie theory is used to simulate scattering by spherical particles. Importantly, our principal component analysis demonstrates that the use of HGR approximations for data analysis would result in the loss of 14-40% of the information contained in a measurement at most instrumental noise levels.

c) **Next steps:** Our next steps will be to embed our radiative transfer modeling framework within a retrieval algorithm like Optimal Estimation that can combine various synergistic measurements of an exoplanet with a priori information available about it, with a rigorous, inbuilt uncertainty quantification mechanism.



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