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Direct imaging of cold exoplanets. A theory framework for atmospheric characterization

Óscar Carrión-González (1), Antonio García Muñoz (1), Juan Cabrera (2), Szilárd Csizmadia (2) and Nuno Santos (3)
(1) Technische Universität Berlin, Germany, (2) Deutsches Zentrum für Luft- und Raumfahrt, Germany, (3) Universidade do Porto, Portugal
(o.carriongonzalez@astro.physik.tu-berlin.de)

Abstract

Upcoming space missions such as WFIRST and under-development concepts like LUVOIR or HabEx will measure the starlight reflected from cold and temperate exoplanets by direct imaging. Reflected starlight is sensitive to atmospheric depths that cannot be probed in transit (e.g. [1]) and provides a means for investigating non-transiting exoplanets. Directly imaged exoplanets observed in reflected starlight represents the next frontier in exoplanet atmospheres characterization. Thus, the theory for planning and interpreting future observations and the physics behind them is now in development [2].

A variety of physical processes affect the light reflected from an exoplanet. Some of the relevant processes are related to the atmosphere itself. Others are not atmospheric in nature but still affect our interpretation of the observations, such as the orbital solution of the planet. The effect of these processes and their uncertainties on the measured signal is potentially degenerate, and result in uncertainties in the atmospheric characterization of the planet [3].

The goal of this work is to understand what information can be extracted from direct imaging observations of exoplanets in reflected starlight and how robust these conclusions are. We computed synthetic spectra for more than 3 million atmospheric configurations that probe a variety of physical properties of the atmosphere. With that, we studied how degeneracies between parameters affect the atmospheric retrieval in direct imaging observations.

1. Introduction

The starlight reflected by an exoplanet is characterized by a planet/star contrast ratio:

$$\frac{F_p}{F_*} = \left(\frac{R_p}{r}\right)^2 A_g(\lambda)\ \Phi(\alpha, \vec{p}) \qquad (1)$$

where F_p and F_* are the planet and star brightness, respectively; R_p is the planetary radius; r is the planet-star distance; A_g is the geometric albedo and $\Phi(\alpha, \vec{p})$ is the planet's scattering phase function, which describes the variation of the planet brightness with phase angle at each wavelength. $\Phi(\alpha, \vec{p})$ depends on the star-planet-observer phase angle α as well as on the vector $\vec{p}$ of physical parameters that describe the planetary atmosphere.

2. Atmospheric model

We created a simple yet physically realistic model of a gas-giant atmosphere, dominated by H_2-He and including a cloud layer as well as an absorbing gas, namely CH_4. The complete set of physical parameters describing the atmosphere is detailed in Eq. (2) and a sketch of the model is shown in Figure 1.

$$\vec{p} = (\tau_{cloud}, \tau_{above}, r_{eff}, f_{CH_4}, \Delta H_{cloud}, \omega_0) \qquad (2)$$

Here τ_{cloud} is the optical depth of the cloud and τ_{above} is the optical depth between the top of the cloud and the top of atmosphere, thus accounting for the vertical position of the cloud layer. r_{eff} is the effective radius of the aerosol particles, f_{CH4} is the methane abundance in the atmosphere, ΔH_{cloud} is the vertical geometrical extension of the cloud and ω_0 is the single-scattering albedo of the cloud aerosols.

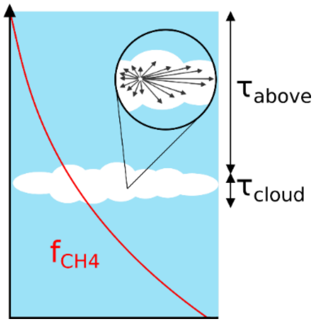

Figure 1: Sketch of the atmospheric model.

3. Results

3.1 Synthetic spectra

By changing the values of the parameters described in (1) and (2), we created a grid of more than 3 million different atmospheric configurations. For each of them, the radiative transfer equation for multiple scattering was solved and synthetic spectra were generated in the optical-near-infrared (500-900nm). We used for that a previously validated radiative transfer code [4].

3.2 Retrieval

After taking one atmospheric set-up as a reference, we tried to retrieve its spectrum among the whole grid. To quantify how well the retrieval was constrained, we calculated the χ^2 figure-of-merit on every spectrum with respect to the reference one. This way we could confirm the degeneracy amongst parameters, which might cause different atmospheric configurations to show very similar spectra. We performed this analysis adding noise to the reference spectrum with several levels of signal-to-noise ratio.

Since F_p/F_* are multidimensional-dependent results, χ^2 is also a multidimensional function. We projected χ^2 into 2D maps to study the degeneracies between each pair of parameters separately. In Figure 2 we show one of these 2D χ^2 maps for the pair of parameters τ_{cloud} - ω_0 and a specific atmospheric configuration.

4. Summary and Conclusions

Our results allow us to quantify the degeneracies that physical parameters produce in the spectra of directly imaged exoplanets observed in reflected starlight. The study is timely since such planets will be observed by future missions like WFIRST, LUVOIR or HABeX.

Acknowledgements

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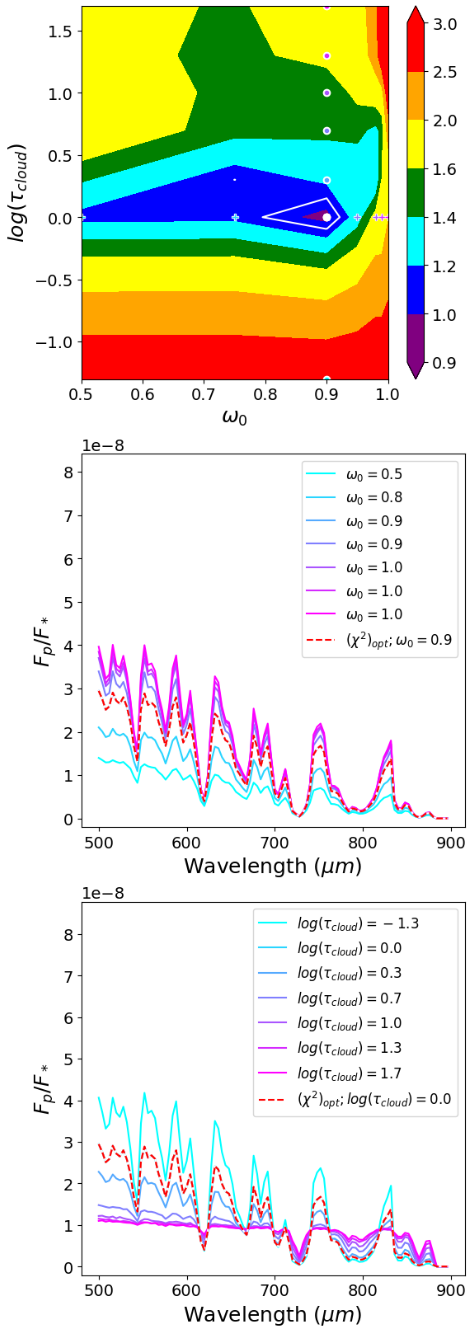

Figure 2: Up: 2D χ^2 map for τ_{cloud} and ω_0, with the best fitting configuration marked by a white dot. Middle: changes in F_p/F_* when only ω_0 varies. Bottom: changes in F_p/F_* when only τ_{cloud} varies.