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Clouds on hot Jupiters: implications for transit spectroscopy

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Abstract

Since the first detection of a planet orbiting another main sequence star, hundreds of extrasolar planets have been confirmed and more than 2000 candidates have been identified. To date, the best-characterised class of planets using this method are the 'hot Jupiters', and evidence is now emerging that these hot planets have cloudy atmospheres. Clouds and aerosols have a large impact on the spectroscopic signatures and radiation balance of the planets in our own solar system; this is also true for brown dwarfs, which exist at similar temperatures to the hottest of the giant exoplanets. We investigate the effect of different types of cloud on the transmission and eclipse spectra of hot Jupiters, and will thereby explore ways of breaking degeneracies between different model atmosphere scenarios.

1. Introduction

One of the most successful methods of exoplanet detection has been via planetary transits, when the planet crosses its host star from the point of view of an observer and the resultant drop in total flux from the system can be measured. Planetary transits also provide the opportunity to study the atmospheres of extrasolar planets; if the transit of a planet across the stellar disk is observed at multiple wavelengths, an additional drop in flux at some wavelengths due to the presence of atmospheric absorbers may be seen, and a transmission spectrum of the planet's atmosphere is measured. When the same planet is eclipsed by its host star, its emission spectrum may be extracted by comparing the in eclipse flux at each wavelength (flux from the star only) with the flux just outside eclipse (combined star and planet contributions).

Hot Jupiters have strong signals in transmission and eclipse as they have extended atmospheres, are large and hot, and are also likely to be observed in transit as they are close to their host stars. Attempts at detailed atmospheric characterisation have so far been hampered by sparse, low-resolution datasets separated in time and spectral range that have proven difficult to stitch together [5]. The arrival of the James Webb Space Telescope (JWST) and dedicated missions such as the Exoplanet Characterisation Observatory [6] (EChO) will be invaluable in overcoming this problem, but the lack of ground truth and model degeneracies (multiple atmospheric scenarios providing an equally good fit to observations) will then become the limiting factors [1].

All the planets in our solar system that have substantial atmospheres also have some form of haze or cloud, with widely different compositions, structures and particle sizes, which impact the way in which they scatter and absorb light. Understanding the behaviour of clouds on these bodies is crucial for interpreting their visible and infrared spectra; they also play an important role in planetary radiation balance and therefore climate. Their complexity, coupled with a lack of ground truth or a priori knowledge, makes exoplanetary cloud a fascinating challenge for the interpretation of transit spectra. The primary transit spectrum of the hot Jupiter HD 189733b contains features attributed to cloud [5], as do observations of the warm super-Earth GJ 1214b, e.g. [3, 1], but since plausible atmospheric scenarios occupy a large region of model parameter space detailed characterisation is not an easy task.

2. Modelling

We use the NEMESIS radiative transfer and retrieval tool [2] to investigate the effects of scattering cloud on the transmission and eclipse spectra of hot Jupiters. A bulk H_2-He atmospheric composition is assumed, with absorption by trace amounts of molecular and atomic species, including H_2O, CO_2, CO, CH_4, NH_3, Na, K, TiO and VO. We also include Rayleigh scattering and collision-induced absorption by H_2 and He. We compute single-scattering transmission spectra (once a photon from the star is scattered by the planet's atmosphere it is lost), and full multiple-scattering, disc-integrated, combined emission/reflection spectra.

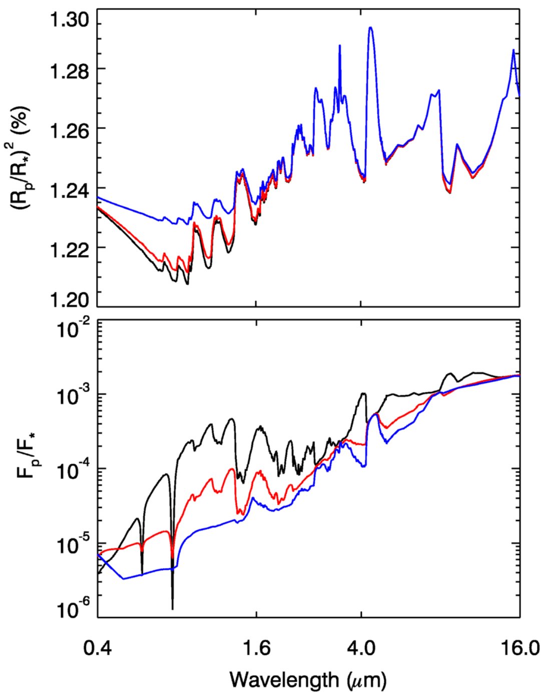

Figure 1: Synthetic spectra for a hot Jupiter 0.1 AU from a G2 star in transmission (top) and eclipse (bottom). The cloud is between 100 and 1 mbar, with a constant aerosol number per gram of atmosphere, and a complex refractive index similar in form to that of enstatite. Black/red/blue lines are for log-normal size distributions of width 0.25 and modal radii of 0.1/1.0/3.0 μm respectively.

Many potential cloud constituents for hot Jupiters have been suggested, mostly based on those expected to occur on brown dwarfs [4]. The composition of cloud particles is relatively unimportant if single scattering is assumed, but for multiple scattering calculations the complex refractive index of the cloud-forming material has a large effect on the scattering behaviour. To investigate this, we use a range of wavelength-dependent real and imaginary refractive indices, that include characteristic features of proposed cloud constituents such as $MgSiO_3$ (enstatite), MnS, ZnS, Na_2S and KCl. We produce a range of synthetic transmission and eclipse spectra for hot Jupiters with different complex refractive indices of the cloudy material, cloud particle size distributions, vertical cloud distributions and optical depths. We investigate the impact of these properties on the shape of the spectra, and examples for different particle size distributions are shown in Figure 1.

We also explore the degeneracies between cloud variability and temperature/gas abundance variability; [3] and [1] find that multiple scenarios with different cloud and trace gas abundances produce an equally good fit to observed spectra of the super Earth GJ 1214b, making it impossible to distinguish between them. Therefore, assumptions about cloud properties are likely to affect estimates of atmospheric composition and temperature structure for hot Jupiters.

3. Summary

Variation in the cloud parameters of our hot Jupiter atmospheric model has a significant impact on the shape of transmission and eclipse spectra (Figure 1), with implications for attempts to constrain temperature structure and gaseous abundances from such observations. A detailed mapping of the cloud parameter space will be crucial for the successful interpretation of transit spectra from future missions such as EChO and JWST, in order to account for degeneracies in the retrieval problem.

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