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Unravelling the biases of transmission spectroscopy due to the three-dimensional structure of exo-atmospheres

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Abstract

1. Introduction

On the road to understanding the chemical composition, nature, and evolution of exoplanet atmospheres, Ultra hot Jupiters are interesting systems: with dayside atmospheres hotter than 2,200 K and nightsides cooler than 1600 K they are host to two completely different atmospheric regimes [1].
Transmission spectroscopy provides us with information on the atmospheric properties at the limb, which is often intuitively assumed to be a narrow annulus around the planet. This is why all existing retrieval algorithms used so far to constrain the atmospheric composition from data rely either on i) a single 1D forward model, thus assuming a uniform limb or ii) a linear combination of 1D models to account for heterogeneities between different regions of the limb (e.g. east vs. west). Even full three-dimensional atmospheric models (GCMs) commonly use only the atmospheric columns at the terminator to predict the observable transmission spectrum for a given simulation. Here, we will demonstrate that the region probed in transmission actually extends significantly toward the day and night sides of the planet and that, as a result, the real transmission spectrum computed from a GCM simulation with our new fully 3D radiative transfer differs significantly from results obtained with the usual assumptions. This comes from the fact that the terminator of hot, synchronously rotating planets is a region exhibiting sharp thermal and compositional gradients. Finally using both real-planet examples and more idealized case, we will demonstrate how this effect can lead to strong biases is the temperature and abundances retrieved from actual data biases that will need to be addressed and corrected for if we want to be able to make robust inferences from future JWST [2] and ARIEL data.

2. Observationnal chain

To characterize the biases due to the full three-dimensionnal atmosphere, we use an observationnal chain composed by 3 models. The first step of this chain begins with modelling the atmospheric thermal structure of the Ultra Hot Jupiter (UHJ) Wasp-121b using the Global Circulation Model (GCM) SPARC/MITgcm [5]. We assume an atmospheric composition of H_2, He, H_2O and CO. As in other model [4] [6] [7] molecular species thermally dissociates at low pressure and high temperature but we assume in the work that only H_2O can dissociate.
Then, we calculate the transmission spectrum of Wasp-121b using Pytmosph3R [3] which is designed to compute transmission spectra based on 3D atmospheric simulations performed with GCM. It produces transmittance maps of the atmospheric limb at all wavelength that can then be spatially integrated to yield the transmission spectrum.
Finally, we used the 1D TauREx retrieval code [8] [9], assuming an isothermal atmosphere for two scenarios: a reference scenario with a constant water abundance at all pressure, and our nominal model containing water dissociation. We vary 4 parameters in our retrieval: H_2O and CO abundances, isothermal temperature, and radius of the planet. While CO is not detectable, we demonstrate that we can measure the temperature and the water abundance.

3. Structure of Wasp-121b atmosphere

The thermal structure of Wasp-121b and the abundance in water which result from it are shown in Fig. 1. Note that the second case treated has the same temperature structure as the first one but with water constant everywhere. As we can see, the atmosphere is strongly

inflated in the dayside of the planet because of the really high temperature. Water is absent from the dayside atmosphere but present on the nightside. Inside a water absorption band (e.g. as probed by HST/WFC3), the transmission spectrum will therefore be sensitive to the cold nightside conditions. The CO abundance, however, remains constant in all the atmosphere. As a consequence, inside a CO absorption band (e.g. as probed by Spitzer), the transmission spectrum will be sensitive to the hot dayside conditions.
When retrieving the 3D spectrum whiten a 1D framework, we show that the abundance ratio of H_2O and CO, hence the C/O ratio is strongly biased towards larger than expected values by the presence of dissociation.

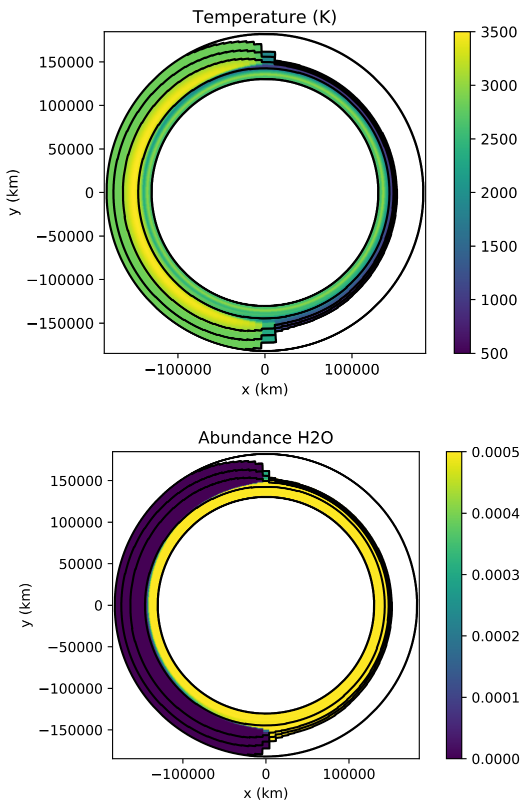

Figure 1: Temperature (top) and water abundance (bottom) of the SPARC/MITgcm of WASP-121b. Note that the radius of the planet and the atmosphere are shown to scale. From center outward, the 5 solid lines are respectively the 10^7, 10^3, 1, 10^{-2}, and 10^{-4} Pa pressure levels. Water is present on the nightside but not on the dayside.

4. Summary and Conclusions

We show that 1D retrieval models fail to retrieve exact abundance values when both vertical and horizontal molecular abundances are present. When abundance and temperature correlate, the transmission spectrum cannot be well represented by a 1D model. A more sophisticated framework needs to be developed to interpret correctly future, higher quality observations from JWST and Ariel.

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