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Remote sensing of exoplanetary atmospheres with ground-based high resolution near-infrared spectroscopy

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Abstract

Thanks to the advances in modern instrumentation we learned about many exoplanets that spawn a wide range of masses and composition. Studying their atmospheres provides insight into planetary diversity, origin, evolution, dynamics, and habitability. Present and future observing facilities will address these important topics in very detail by using more precise observations, high-resolution spectroscopy, improved analysis methods, etc. In this work we investigate the feasibility to retrieve the vertical temperature distribution and molecular abundances from expected exoplanet spectra in the near infrared using the test case of CRIRES+ instrument at the Very Large Telescope (ESO, Chile). We present determinations of optimal wavelength coverage and observational strategies to increase accuracy in the retrievals of atmospheric structures of Hot Jupiters from emission spectra and list potential targets.

1. Introduction

Studying exoplanetary atmospheres is usually done with the help of spectroscopic and photometric observations from space and from the ground. Photometric observations are the most efficient ones in terms of the observing time needed to achieve a required signal-to-noise ratio (SNR) for the exoplanetary atmosphere compared to spectroscopy. Present photometric observations has been used for the detailed analysis of brightest and largest exoplanets called Hot Jupiters (HJ) [1, 2, 3].

Spectroscopic techniques, on another hand, are capable of resolving individual molecular lines but require much longer observing times. This often results in data which is of insufficient quality for quantitative atmospheric retrievals but is good enough to detect the presence of many molecules via, e.g., cross-correlation technique [4, 5]. However, with the advent of future instrumentation, accurate shapes of atmospheric lines on diverse exoplanetary atmospheres could be acquired. This will open a way to constrain atmospheric chemistry, global circulations (winds), and signatures of trace gases produced by possible biological activity.

Our main goal is to investigate the feasibility to retrieve the vertical distribution of the temperature and molecular abundances from expected exoplanet spectra in the near infrared at very high resolution. We focus our research on Cryogenic high-resolution IR Echelle Spectrometer (CRIRES+) on the Very Large Telescope scheduled by the end of 2019 for the European Southern Observatory (ESO)[6]. The instrument will operate between $0.9-5.3$ μm with a highest achievable resolving power of R=100 000.

2. Methods, results and conclusions

In our retrieval approach we use an algorithm based on Optimal Estimation (OE) [7] which has been widely used to study atmospheres of solar system planets [8, 9] and also exoplanets [3]. For our forward model we employed an adapted version of the τ-REx (Tau Retrieval for Exoplanets) software package [2]. We studied several cases of simulated observations at different spectral bands, their combinations, spectral resolving powers, and SNRs. The detailed results of this investigations can be found in [10]. As an example, our Fig. 1 shows the retrieved temperature and molecular mixing ratios from a combination of two spectral regions which would correspond to the two separate settings of CRIRES+.

It is seen that the spectra of HJs in the wavelength range of CRIRES+ is sensitive to a very wide range of atmospheric pressures between 1 bar and 10^{-4} bar. Avoiding regions with strong telluric contamination, the best region to derive mixing ratios of H_2O, CO, and CO_2 is around 1.6 μm and 2.3 μm. In these regions the efficiency of CRIRES+ detectors is also expected to be the highest. We estimate that, in order to carry out detailed retrievals of atmospheric struc-

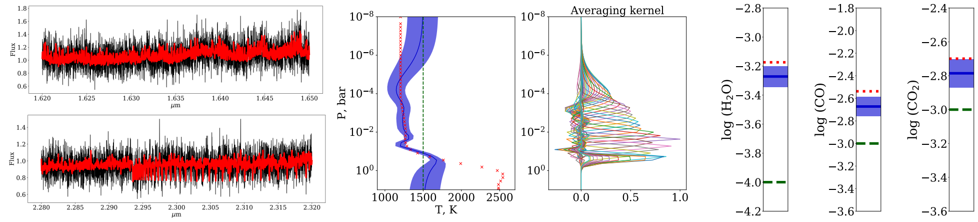

Figure 1: Retrieved temperature and mixing ratios of three molecular species from two spectral regions $1.50 - 170$ μm and $2.28 - 2.38$ μm, respectively. The first two vertical plots compare best fit predicted spectrum of the atmosphere of a selected HJ (red) with the simulated observations (black) assuming SNR=10. The second plot is the temperature distribution as a function of atmospheric pressure shown with full blue line and with error bars shown as shaded area. Red crosses and green dashed line are the true solution and initial guess, respectively. Third plot shows averaging kernels derived for the temperature distribution. Here averaging kernels for different atmospheric depths are randomly color coded for better representation. Next three plots are the values of the retrieved mixing ratios of molecular species (color coding is the same as in the second plot). Note that mixing ratios were assumed to be constant with atmospheric depth and we show their values on the y-axis.

ture, the minimum SNR of the exoplanetary spectrum should be SNR(planet)≈10. The latter depends on the flux contrast between the star and the planet (typical values are on the order of $\approx 10^{-3}$ for HJs) implying the combined spectrum of the star and the planet must have SNR≈10 000. Obtaining such a high SNR is challenging. We will present the potential targets in this contribution along with optimal observing strategies.

Our study suggests that even though the spectra of exoplanets will likely be obtained with very high noise level, the atmospheric retrievals can still benefit from numerous molecular lines observed thanks to wide wavelength coverage of CRIRES+ enabling simultaneous line analysis. This opens a way towards accurate retrievals of altitude dependent quantities, such as, e.g., atmospheric temperatures and molecular abundances.

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