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From spectra to atmospheres: solving the underconstrained retrieval problem for exoplanets

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Abstract. Spectroscopic observations of transiting exoplanets have provided the first indications of their atmospheric structure and composition. Optimal estimation retrievals have been successfully applied to solar system planets to determine the temperature, composition and aerosol properties of their atmospheres, and have recently been applied to exoplanets. We show the effectiveness of the technique when combined with simulated observations from the proposed space telescope EChO, and also discuss the difficulty of constraining a complex system with sparse data and large uncertainties, using the super-Earth GJ 1214b as an example.

Keywords. radiative transfer, methods: data analysis, planets and satellites: individual

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1. Introduction

When a planet passes in front of its parent star as seen from the Earth, the resultant reduction in the amount of observed starlight varies as a function of wavelength, depending on the absorptive properties of the planets atmosphere; when the planet is eclipsed by its parent star, a difference measurement can yield its emission/reflection spectrum. However, a lack of a priori knowledge about the planets bulk properties, cloudiness and temperature can make it difficult to find a unique solution. The NEMESIS radiative transfer and retrieval tool (Irwin *et al.* 2008) allows this process to be explored. Barstow *et al.* (2013a) use NEMESIS to assess the feasibility of constraining exoplanet atmospheres with EChO (Tinetti *et al.* 2012), a proposed ESA space telescope designed to observe continuous transmission and eclipse spectra of transiting extrasolar planets between 0.55 and 16 μm.

2. GJ 1214b: current observations

GJ 1214b (Charbonneau *et al.* 2009) is a super-Earth transiting an M dwarf 13 pc away. Despite measurements of transmission through its atmosphere in the visible and infrared from a range of space- and ground-based sources (e.g. Bean *et al.* 2011), little can be inferred about the atmosphere. The flat transmission spectrum could be evidence of an atmosphere with a high molecular weight, but could also indicate a H_2-He atmosphere with high altitude haze or cloud, and the current data are shown to have insufficient signal-to-noise and wavelength coverage to discriminate between these scenarios (Barstow *et al.* 2013b and references therein).

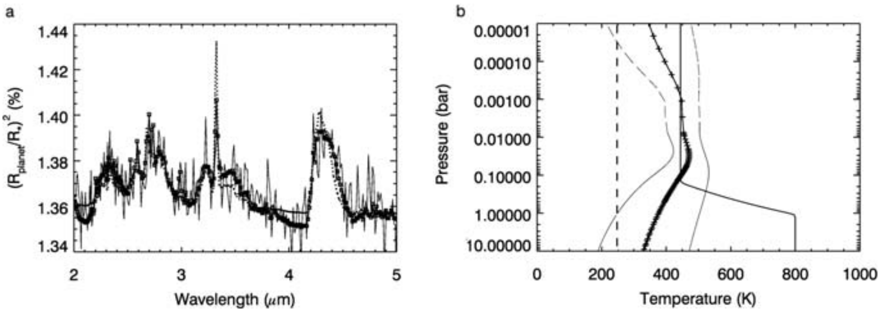

Figure 1. a) The GJ 1214b noisy synthetic transmission spectrum (thin line) for a 50% H_2O atmosphere is fit better by a 50% H_2O model (black line with points) than by a H_2-He model (dotted line). This is particularly evident in the CH_4 band at 3.3 μm and the CO band at 4.3 μm. b) Input temperature (black line) *a priori* temperature (dashed line) and retrieved temperature (crosses) with error (fine dashed lines) for a secondary eclipse retrieval. The correct stratospheric temperature is retrieved but there is no information about the deep atmosphere temperature.

3. GJ 1214b with EChO

Barstow *et al.* (2013a) generate a series of model hot Jovians, using NEMESIS as a forward model to calculate noisy synthetic transmission and eclipse spectra of these, and perform retrieval feasibility tests for EChO observations. Barstow *et al.* (2013b) use a similar technique to demonstrate that, by observing 30 transits of GJ 1214b with EChO, a high molecular weight atmospheric scenario would be excluded if the planet in fact has a cloudy extended atmosphere. Using the same technique and model parameters, we show that if the atmosphere instead contained 50% water vapour, 60 transits would be required to achieve the requisite level of signal and distinguish between the two scenarios. When we add the noise expected for 60 observations to the best fit H_2O-dominated model from Barstow *et al.* (2013b) and fit it with a 50% H_2O model atmosphere, the reduced-χ^2 parameter is 1.05, as opposed to 1.31 if it is fit with a cloudy H_2-He model (Figure 1a shows the fit between 2 and 5 μm). All models are as in Barstow *et al.* (2013b), to which we refer the reader for details. An emission spectrum of GJ 1214b could be obtained with 30 secondary eclipse observations, allowing an observational constraint to be placed on the stratospheric temperature of the planet for the first time and providing information about the albedo and therefore cloudiness of the planet (Figure 1b). EChO will be a valuable mission for the study of transiting extrasolar planets, and space-based spectroscopy over a large wavelength range is important for detailed study of planets like GJ 1214b. Optimal estimation retrieval is shown to be a powerful technique for analysing these data.

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