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Unlocking the Flux Contribution from Unresolved Emission Spectra

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Abstract

To better understand the atmospheric composition and thermal structure of exoplanets we need to consider more realistic models which we can compare with data. The James Webb Space Telescope (JWST) will provide us with the best multiband observations of exoplanet atmospheres to date, hence 2D effects will begin to become important. We explore different retrieval techniques to investigate the impact that varying the contribution from a hot and cold temperature profile has on the retrievability of the chemistry for all of the NIRSpec viewing modes. We conclude that when performing a retrieval on a planetary body with 2 temperature-pressure (TP) profiles will result in chemistry biases if trying to retrieve with a model with 1 TP profile. We proposal a novel method of applying a free parameter to a 1D model which acts to dilute the spectrum, this technique performs just as well as retrieving with 2 TP profiles, with the bonus of reducing the parameter space. This means that the data is not sensitive enough to resolve the colder profile. We find that we need a large wavelength coverage before 2D effects become prominent, and more crucially this wavelength coverage needs to cross the spectral range before the peak of the blackbody function.

1. Introduction

Planets are intrinsically 3D with their temperature, atmospheric composition and clouds varying with latitude, longitude and altitude. However emission spectra models used in retrieval are usually altitude dependent only [5] [2]. Here we show that this leads to biases in the retrieved chemical composition. With the largest wavelength coverage, signal to noise ratio and resolution that is promised by the James Webb Space Telescope these biases will become a real problem when performing retrievals with the observations. Recently [3] investigated the use of 2D retrievals when interpreting WFC3-like and JWST-like data. We extend on this research by investigating which observing strategy of the NIRSpec instrument would be best to disentangle the contributions from the different parts of the dayside to ensure a proper measurement of the atmospheric abundances. We make recommendation on instrument mode choices, wavelength coverage and signal-to-noise that should be used for different planet scenarios. Finally, we propose a single parameter that can account for dayside inhomogeneities and lead to unbiased abundance measurements in most cases with a low additional computational cost.

2. Methodology

We build a uniformly mixed, cloud-free model atmosphere assuming that part of the atmosphere is colder and part of the atmosphere is hotter, we vary the contribution that each part gives to the final spectrum using the following parameterisation:

$$F_{\text{weighted}} = xF_{\text{hot}} + (1-x)F_{\text{cold}} \quad (1)$$

where F_{hot} is the 1D spectrum generated from the hot TP profile and F_{cold} is the 1D spectrum generated from the cold TP profile. x represents the weight applied to the hotter profile and is a free parameter in our 2D retrievals we use x = 0.8, 0.6, 0.4 and 0.2. This can be representative of the dayside emission and also emission observed at different points in phase. For this study we fix the TP profiles to have a large contrast.

2.1. Our Model

We use the **N**on-linear optimal **E**stimator for **M**ultivariat**E** spectral analy**SIS** code (NEMESIS) [4] to perform our forward modelling efforts. For the retrievals conducted in this study we have wrapped our forward model in a Bayesian framework, namely using a nested sampling approach [6].

2.2. Spectral Grid

We generate the wavelength grid and noise [1] for the NIRSpec Prism (0.6 - 5.3μm), NIRSpec G395M (2.87 - 5.10μm), NIRSpec G235M (1.66 - 3.07μm) and NIRSpec G140M (0.97 - 1.84μm) for one eclipse observation. For NIRSpec Prism (nominal resolving power$\sim$100) we use the resolution of the largest bin step and for the different NIRSpec

	80%				60%		
	2TP	Dilution	1TP		2TP	Dilution	1TP
NIRSpec G140M	1.85σ U	2.11σ B	B	NIRSpec G140M	4.58σ U	4.52σ U	B
NIRSpec G235M	1.97σ U	$< 1\sigma$ U	U	NIRSpec G235M	4.56σ U	4.46σ U	B
NIRSpec G395M	$< 1\sigma$ U	$< 1\sigma$ U	U	NIRSpec G395M	$< 1\sigma$ U	$< 1\sigma$ U	B
NIRSpec Prism	9.89σ U	9.64σ U	B	NIRSpec Prism	17.06σ U	17.00σ U	B
G235M + G395M	11.11σ U	11.12σ U	B	G235M + G395M	18.94σ U	18.86σ U	B
	40%				20%		
	2TP	Dilution	1TP		2TP	Dilution	1TP
NIRSpec G140M	4.12σ U	4.18σ U	B	NIRSpec G140M	4.53σ U	4.61σ U	B
NIRSpec G235M	4.42σ U	4.32σ U	B	NIRSpec G235M	5.18σ B	5.23σ B	B
NIRSpec G395M	$< 1\sigma$ U	$< 1\sigma$ U	U	NIRSpec G395M	2.77σ U	2.36σ U	B
NIRSpec Prism	19.16σ U	18.9σ U	B	NIRSpec Prism	16.15σ U	16.03σ U	B
G235M + G395M	21.31σ U	21.31σ U	B	G235M + G395M	18.57σ U	18.64σ U	B

Table 1: The results for all the test cases and instrument modes for the 3 retrieval styles used in this study. We calculated the Bayes factor of the 2TP and dilution with respect to the 1TP approach (difference in the ln(Z) values) and then converted this to a significance estimate for the detection of more complex models in terms of sigma. We consider a strong detection if $>3.6\sigma$. The letters U and B indicate whether the retrieval was either biased or unbiased in terms of chemistry. All models had a reduced χ^2 of below 1.

grisms (nominal resolving power$\sim$1000) we use a resolution of R=100. We choose to focus this study on the various NIRSpec instrument modes as these will be used for transiting exoplanet observations and also provide a large overlapping wavelength grid. We decided to also use the medium resolution grisms (R$\sim$1000) as opposed to the higher resolution grisms (R$\sim$2700) to test the lower limits of the SNR needed.

3. Results

We aim to show which atmospheric retrieval was most appropriate in retrieving on an atmosphere which has 2 TP profiles. We retrieve the 2TP model with 3 different retrieval styles: a 1D model, a 1D model with a free parameter which is able to dilute the spectrum ($F_{\text{dilution}} = sF_{\text{average}}$) and then a model with 2 TP profiles. The results of these simulations are shown for the different values of x in Table 1. We show that for the majority of the retrievals, a 1D model was not able to accurately measure the abundances in the atmosphere (i.e shown with B for bias chemistry). However, we find that the correct atmospheric abundances are obtained when either using the full 2TP retrieval or the diluted retrieval (i.e shown with U for unbiased chemistry).

4. Summary and Conclusions

We conclude that trying to retrieve a planetary atmosphere with a 1D model will result in biased chemistry if the true observations are not 1D. These results will help us select preferred viewing modes for future observations.

We show that a novel method of applying a dilution factor to a 1D model can provide a similar retrieval capability as using 2 TP profiles, this suggests that it would be ideal to use as a technique for studying the chemistry of a quenched atmosphere while saving on computation time, this is because it has the capability to perform the same as either a 1D retrieval (if the dilution factor =1) or a 2D retrieval (if the dilution factor $\neq$ 1) without facing biases in the chemistry. The posterior distributions show us that the dilution factor appears to imitate the contribution of the most dominant flux (or similar to this).

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