Exoplanet Characterisation Observatory (EChO)

Assessment Phase Payload Study

EChO Atmospheric Retrieval Technical Note

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1 PREAMBLE

1.1 SCOPE

This document covers the spectroscopic retrieval process to be used in the analysis of EChO data.

1.2 PURPOSE

This document provides detailed information about the spectral inversion techniques being developed at the University of Oxford, for the benefit of the EChO community.

1.3 APPLICABLE DOCUMENTS

AD #	APPLICABLE DOCUMENT TITLE	DOCUMENT ID	ISSUE / DATE
1			
2			
3			

1.4 REFERENCE DOCUMENTS

RD #	REFERENCE DOCUMENT TITLE	DOCUMENT ID	ISSUE / DATE
1			
2			
3			

1 INTRODUCTION

EChO is expected to provide visible and infrared transmission and disc-integrated emission/reflection spectra for a range of transiting extrasolar planets. These spectra will simultaneously cover the wavelength range from 0.55–11 μm in the baseline case (goal 16 μm) at a far higher precision than is achievable with ground-based observatories. With these spectra, we hope to unambiguously characterise the atmospheric structure and composition of EChO's target population.

Optimal estimation is a technique used to infer the atmospheric state from spectra; it has been used successfully over many years to place constraints on the nature of solar system planetary atmospheres, and more recently has been applied to hot Jupiters such as HD 189733b (e.g. Lee et al. 2012, Line et al. 2012). NEMESIS (Irwin et al. 2008) is an atmospheric radiative transfer and retrieval tool that utilises a non-linear optimal estimation algorithm to iteratively find the best-estimate atmospheric state for spectroscopic measurements.

This note describes the use of NEMESIS to test the accuracy and precision with which EChO could determine the atmospheric states of various, hypothetical, transiting Jovian planets (Table 1). We use estimates of the expected EChO signal-to-noise ratio in the photon-limited case to generate noisy synthetic 'observed spectra', which we then feed back into NEMESIS in order to perform a retrieval; a comparison of the input with the inferred atmospheric state indicates the extent to which the atmosphere can be uniquely constrained from the information in the spectrum. Much of this material is reproduced from Barstow et al. 2013.

Planet	Mass (10^24 kg)	Radius (km)	Star type	Distance	Average single eclipse SNR
Hot Jupiters	1800	75000	G2	35 pc	~5
Warm Jupiter	1800	75000	G2	35 pc	~0.4
Hot Neptune	180	30000	M5	6 pc	~6

Table 1: Properties for the hypothetical planets in the feasibility test. The SNR given is the average SNR per spectroscopic channel across the wavelength range, for one eclipse (Barstow et al. 2013).

2 RETRIEVAL FEASIBILITY TESTS

In order to examine the level of information about exoplanet atmospheres that would be available from EChO, Barstow et al. (2013) use NEMESIS to generate a series of synthetic spectra based on a range of model planets. The large parameter space is initially reduced to four planet cases (Table 1): a hot Jupiter-size planet, a hot Jupiter-size planet with a temperature inversion and a warm Jupiter-size planet, all orbiting a Sun-like star at 35 pc (order-of-magnitude fainter than brightest target requirement), and a hot Neptune-size planet orbiting an M5 star at 6pc (2x brighter than faintest target requirement). Belu et al. (2011) state in their study for JWST that they expect ~10 transiting hot Jupiters out to 50 pc; the faintest sun-like star to be observable by EChO should be visible out to 150 pc, so there should be ~200-300 similar hot Jupiters within observable range. Bonfils et al. (2011) estimate that 3 out of every 100 M dwarfs would have a hot Neptune in orbit, and there are around 1000 bright M dwarfs (J<10) known within 16 pc (Lepine et al. 2011), so assuming a transit probability of ~1/30 at least one hot Neptune should be observable by EChO. We would also expect several super-Earth sized planets to be observable around this kind of star.

Primary (transmission) and secondary (eclipse) transit spectra can be calculated for the four planet cases. The temperature profile and bulk composition (90% H_2 and 9.9% He) are fixed, but the abundances of 5 trace gas species (H_2O, CO_2, CO, CH_4 and NH_3) are allowed to vary over the concentration range 0.1–1000 ppmv. Between 100 and 500 synthetic transit and eclipse spectra were calculated for each test scenario, each with different uniformly distributed trace gas volume mixing ratios (VMRs), and Gaussian random noise at the photon limit for EChO was added to the spectra. These were then fed back into NEMESIS and the VMRs for each of the 5 trace gases were retrieved, along with temperature as a function of atmospheric pressure in the eclipse case.

2.1 SENSITIVITY TO ATMOSPHERIC PARAMETERS

The sensitivity to temperature as a function of pressure and trace gas VMRs for each spectral bin in primary and secondary transit is shown in Figure 1. Eclipse spectra are more sensitive to temperature as a function of pressure than are transmission spectra, and transmission spectra cannot be used to independently constrain the temperature structure of the atmosphere. It can be seen that absorption lines due to different gases overlap with each other, indicating that degenerate solutions may exist.

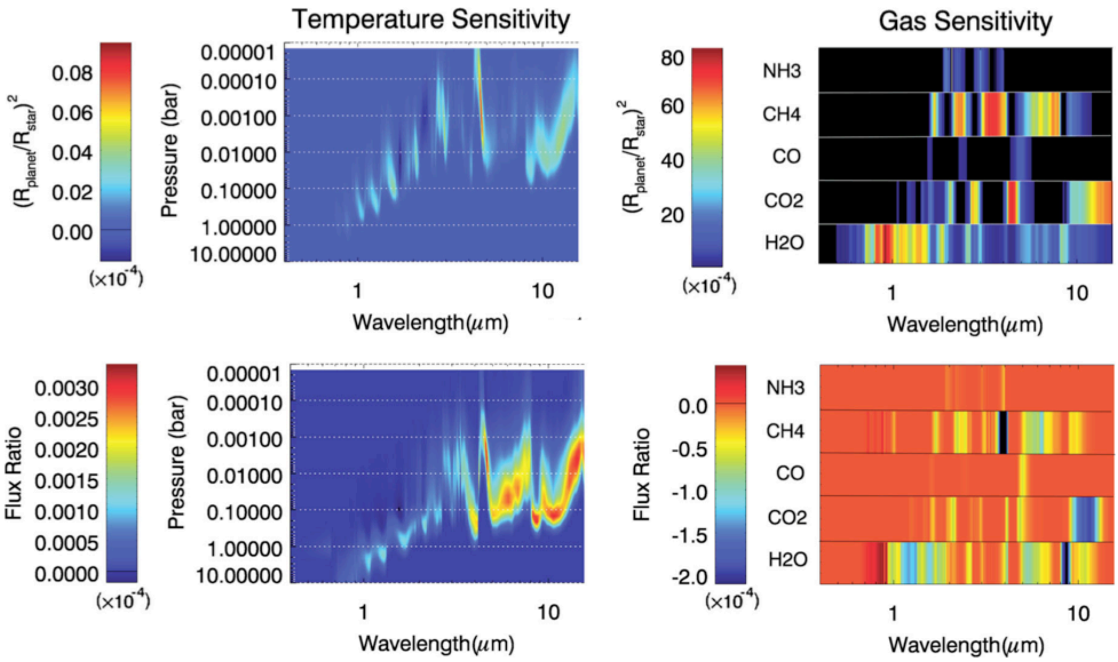

Figure 1: Sensitivity of the measured quantity to variations in the atmospheric state for primary transit (top) and secondary transit (bottom). Taken from Barstow et al. (2013).

3 FEASIBILITY TEST RESULTS

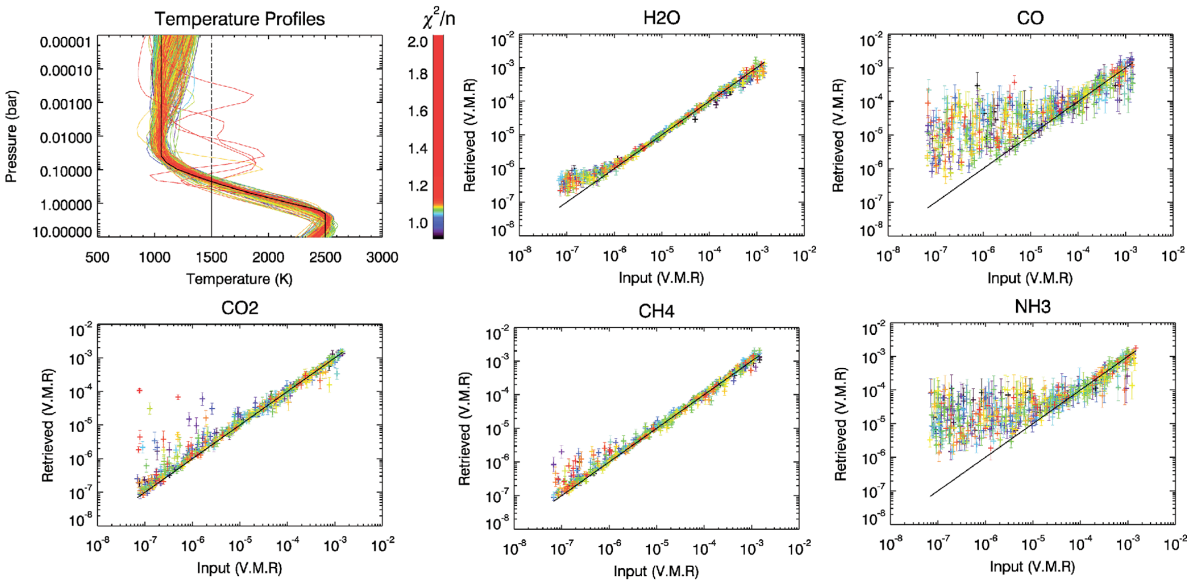

Figure 2: Hot Jupiter eclipse retrieval results. Different colours correspond to different values of the goodness of fit parameter. The solid black line on the temperature plot indicates the true value, and the solid black lines on the gas VMR plots indicate the 1:1 input:retrieved correspondence line. The dashed line in the temperature plot is the *a priori*, and the *a priori* for the gases was 10^-4. Taken from Barstow et al. (2013).

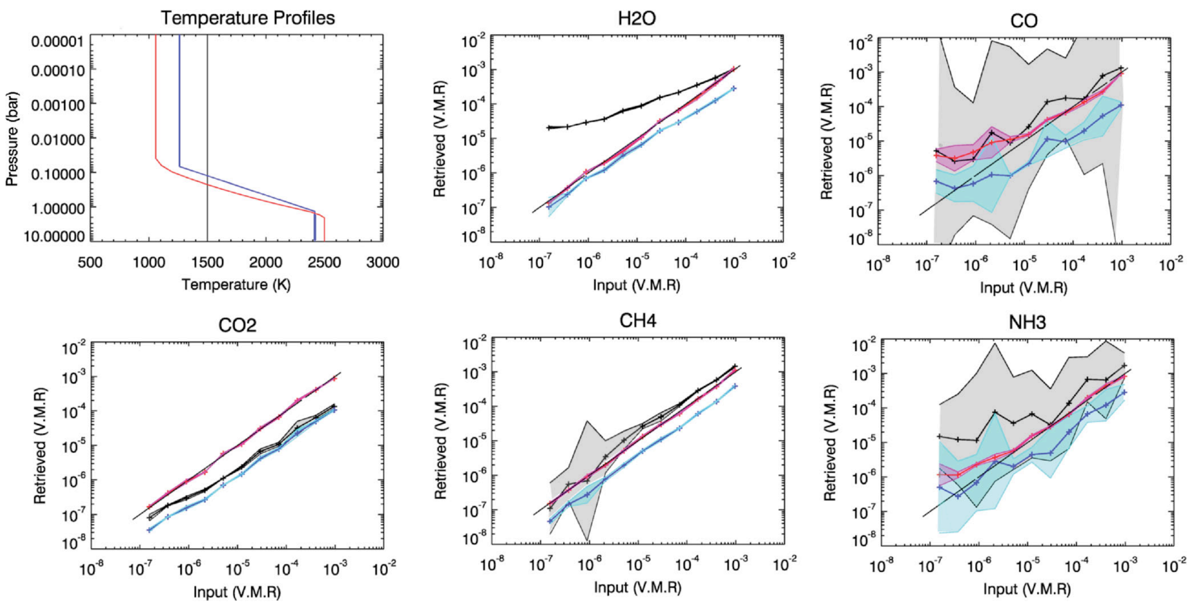

Figure 3: Hot Jupiter transmission retrieval results. Different colours correspond to different input temperature profiles (temperature is not retrieved) averaged over 100 model runs. The solid black lines on the gas VMR plots indicate the 1:1 input:retrieved correspondence line, and the *a priori* for the gases was 10^-4. Taken from Barstow et al. (2013).

Quantity	Hot Jupiter	Warm Jupiter	Hot Neptune
Temperature	200 K (1 bar – 1 mbar)	250 K (0.5 bar – 5 mbar)	100 K (1 bar – 1 mbar)
H_2O	2x (>0.5 ppmv)	4x (>50 ppmv)	2x (>0.5 ppmv)
CO_2	3x (>10 ppmv), 6x (>0.1 ppmv)	5x (>50 ppmv)	2x (>0.1 ppmv)
CO	5x (>100 ppmv)	Not detectable	3x (>10 ppmv)
CH_4	2x (>1 ppmv), 3x (>0.1 ppmv)	4x (>50 ppmv)	1.5x (>0.1 ppmv)
NH_3	5x (>100 ppmv)	Not detectable	3x (>100 ppmv)

Table 2: Precision with which various atmospheric properties can be constrained from a single EChO secondary eclipse observation for a range of test planet cases.

Quantity	Hot Jupiter	Warm Jupiter	Hot Neptune
H_2O	1.5x (>0.5 ppmv)	1.5x (>10 ppmv)	1.5x (>0.1 ppmv)
CO_2	1.5x (>0.5 ppmv)	2x (>50 ppmv)	1.5x (>0.1 ppmv)
CO	Not detectable	Not detectable	1.5x (>10 ppmv)
CH_4	1.5x (>0.5 ppmv)	2x (>10 ppmv)	1.5x (>0.1 ppmv)
NH_3	3x (>100 ppmv)	Not detectable	1.5x (>5 ppmv)

Table 3: Precision with which various atmospheric properties can be constrained from a single EChO primary transit observation for a range of test planet cases (from Barstow et al. 2013).

3.1 HOT JUPITER

We find that it is possible with EChO to retrieve the temperature as a function of pressure and the volume mixing ratios of H_2O, CO_2 and CH_4 to a high precision (Figure 2, Table 2). It is also possible to place upper limits on the mixing ratios of CO and NH_3, although these are more difficult to retrieve due to the high level of contamination from absorption lines of other species.

In transmission, there is insufficient information in the spectrum to independently retrieve temperature (Figure 1), so it becomes necessary to estimate a temperature profile (Figure 3). It is possible that a temperature profile has already been obtained for the dayside, in which case this, or a version modified to account for the expected efficiency of thermal transport from day to night, may be used. If this is not the case, it will be necessary to estimate the profile based on the equilibrium temperature of the planet. If little is known about its atmospheric composition and structure, e.g. the presence of clouds, this is unlikely to be accurate. An isothermal approximation (Figure 3, black/grey) results in a poor retrieval of the gas volume mixing ratios, and even an estimate with the correct shape (blue) doesn't allow a correct retrieval. It is only if the temperature is estimated correctly (red) that the gas volume mixing ratio retrieval is reliable. This is a problem that should be carefully considered for the analysis of EChO data. If an extremely high signal to noise is achieved by averaging over 30 transits for the hot Jupiter, the retrievals for cases where the temperature estimate is wrong have a much higher reduced χ^2 (goodness-of-fit parameter) than the cases where the temperature is estimated correctly. It would therefore be possible to vary the temperature profile and minimise the reduced χ^2, in which case accurate retrievals of gaseous abundances should be possible from transmission spectra (Table 3).

3.2 WARM JUPITER

The warm Jupiter planet is significantly cooler than the hot Jupiter, and so its signal in eclipse orbiting a similar star is much smaller. The signal-to-noise for a single eclipse is too low to reliably constrain the temperature profile and gaseous volume mixing ratios (Table 2). It would therefore be necessary to average over 30 transits in order to constrain the atmosphere state (Figure 4). The signal to noise is also lower in transmission due to the smaller atmospheric scale height of a cooler planet (Table 3).

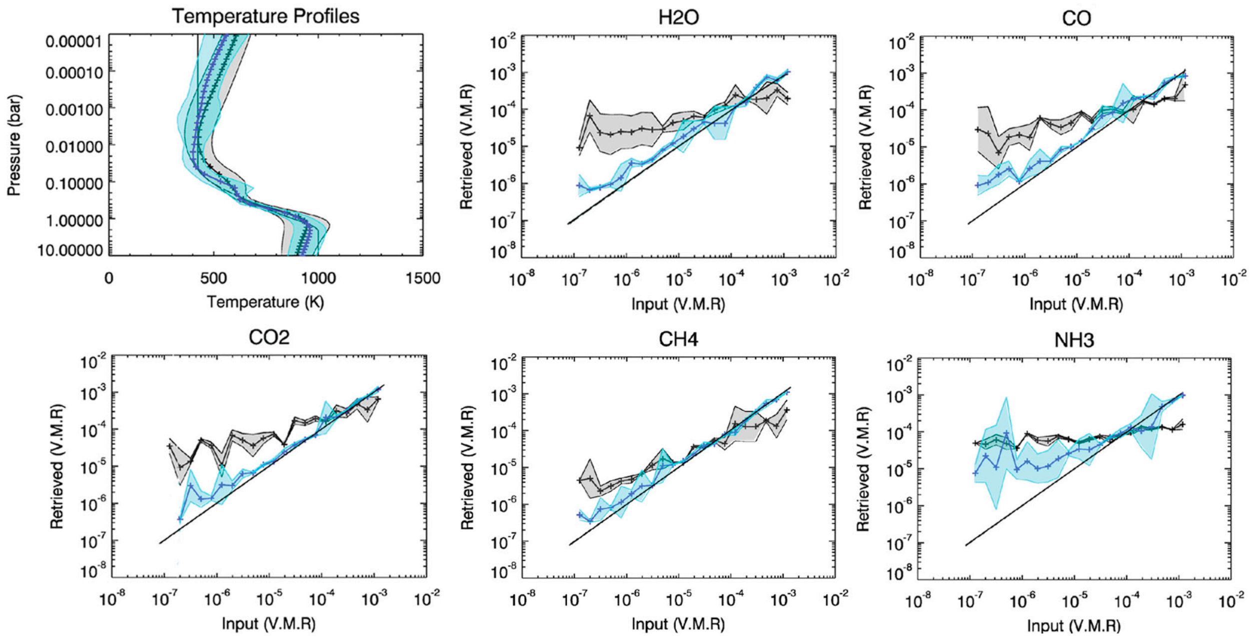

Figure 4: Warm Jupiter retrievals when only a single eclipse is observed (grey) and when the results from 30 eclipses are averaged (blue). It can be seen that the gas volume mixing ratios cannot be retrieved with a single eclipse, but become retrievable when several observations are included (from Barstow et al. 2013)

3.3 HOT NEPTUNE

The hot Neptune is smaller and cooler than the hot Jupiter, but because the M5 star it orbits is small and cool the contrast ratio is very high, and so the temperature and H_2O, CO_2 and CH_4 volume mixing ratios can be retrieved to a high degree of precision except at very low abundances (Figure 5, Table 2). The transmission spectrum also has very high signal-to-noise, so accurate retrievals for these three gases can be easily obtained (Table 3).

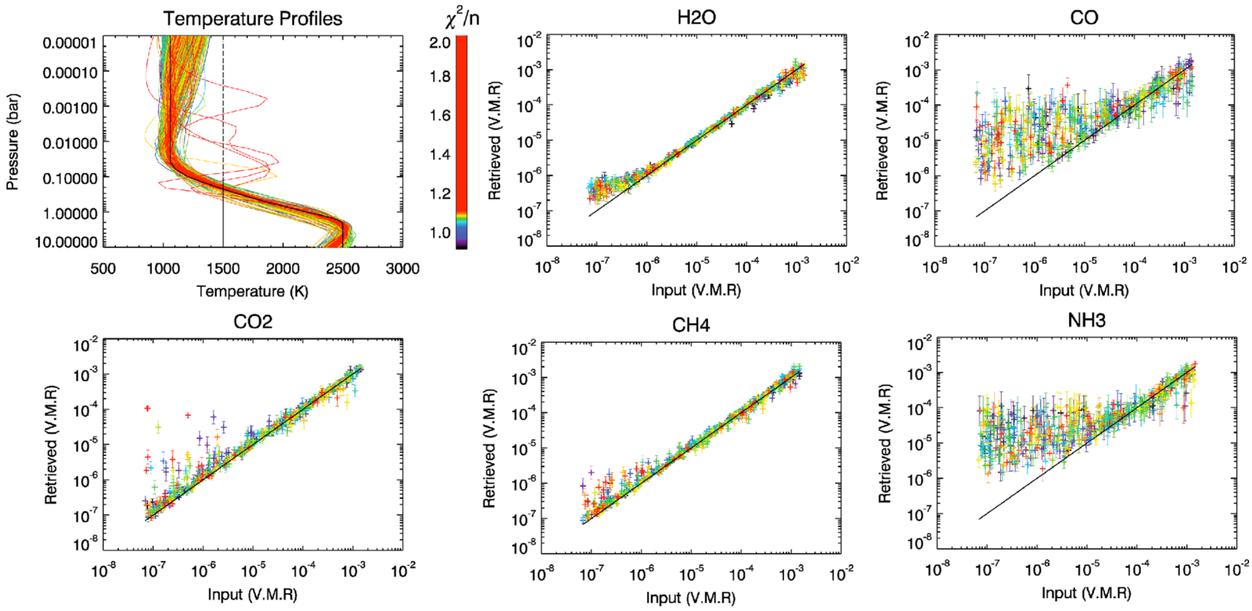

Figure 5: Eclipse retrievals for a hot Neptune orbiting an M5 star (from Barstow et al. 2013).

4 IMPROVEMENTS OVER CURRENT CAPABILITY

Hot Jupiters and Neptunes have strong signals in the near-infrared, but for smaller, cooler planets around redder stars longer wavelength regions will become increasingly important. In addition, the models shown above are simple; the increased complexity of atmospheres containing a broader range of trace gas species and/or clouds will require the broadest possible wavelength range to break degeneracies. Currently, spectra spanning a broad wavelength range can only be obtained by stitching temporally disconnected measurements from different ground- and space-based observatories; the James Webb Space Telescope will also not achieve the same level of instantaneous coverage as EChO, since there is a split at 5 microns between the NIRSpec and MIRI instruments. This is problematic because stellar activity can alter the baseline stellar flux between different measurements, leading to large uncertainties when combining measurements, and this has been particularly problematic for analysing transmission spectra of the super-Earth GJ 1214b. EChO represents the only prospect of overcoming this problem, by instantaneous acquisition of the full visible–mid-IR spectrum, within the next 15 years.

4.1 GJ 1214B

GJ 1214b is the best-studied super-Earth planet, with many ground- and space-based spectroscopic and photometric data (Charbonneau et al. 2009; Bean et al. 2010, 2011; Désert et al. 2011; Croll et al. 2011; Berta et al. 2012; de Mooij et al. 2012; Narita et al. 2012; Fraine et al. 2013). However, the spectrum is very flat within the error bars, and additional uncertainty introduced when temporally and spectrally disconnected measurements are stitched together makes it impossible to constrain its atmosphere with the information available at present. One possible scenario is a cloudy H_2-He atmosphere with an opaque cloud deck; the possibility of retrieving properties of such an atmosphere with EChO is investigated in Barstow et al. (2013b). In Figure 6, synthetic spectra at the resolution and coverage of EChO are shown; it can be seen that the CH_4 and CO_2 bands are very important for distinguishing between different model atmospheres, in particular the CO_2 band at 15 microns.

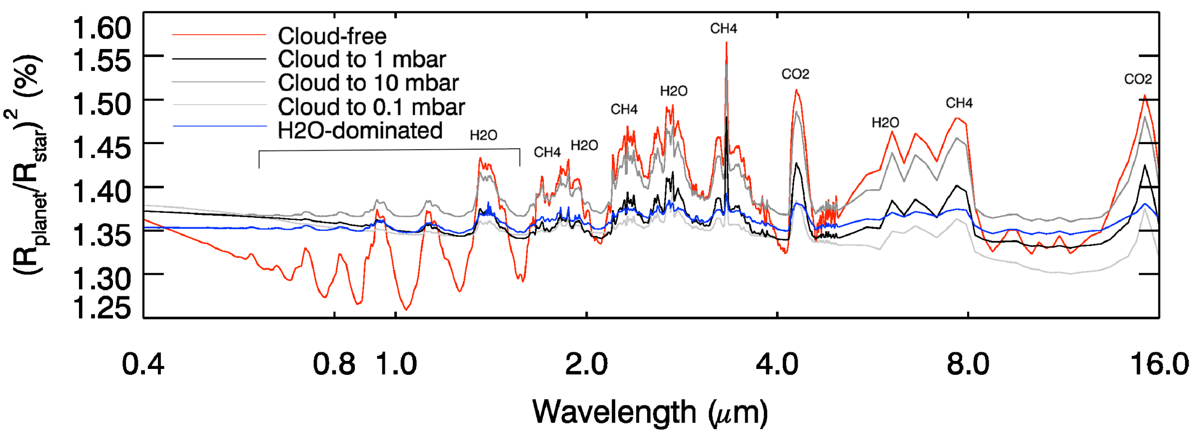

Figure 6: Synthetic transmission spectra at the resolution of EChO for the super-Earth GJ 1214b, with different atmospheric properties. The locations of the principal absorption bands are indicated (from Barstow et al. 2013b).

The star GJ 1214 corresponds to the EChO faintest target requirement case as defined in the MRD, so a demonstration of success with this planet is crucial. Barstow et al. (2013b) find that, over 30 transits of GJ1214b, EChO would be able to distinguish between a cloudy extended atmosphere and a high molecular weight atmosphere (Figure 7). This demonstrates the huge advance in capability that is provided with full, instantaneous spectral coverage.

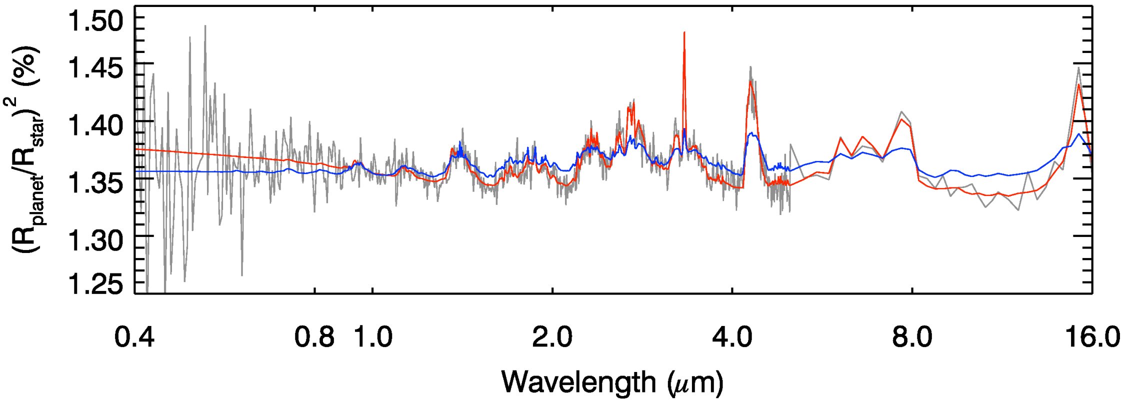

Figure 7: A noisy synthetic transmission spectrum for GJ 1214b in the cloudy H_2-He rich atmosphere case, as seen by EChO. This spectrum can be successfully fit and the atmospheric properties retrieved with an H_2-He model atmosphere (red), but cannot be reproduced with a high molecular weight atmosphere (blue).

Gaining a secondary eclipse observation of GJ 1214b will also be crucial for constraining its atmospheric state, as this is the only thing that can provide an independent measurement of temperature. The stratospheric temperature can be constrained to within +/- 60 K from 30 averaged eclipse observations with EChO (Figure 8), which would be an extremely useful measurement. This cannot be done with any current instrumentation.

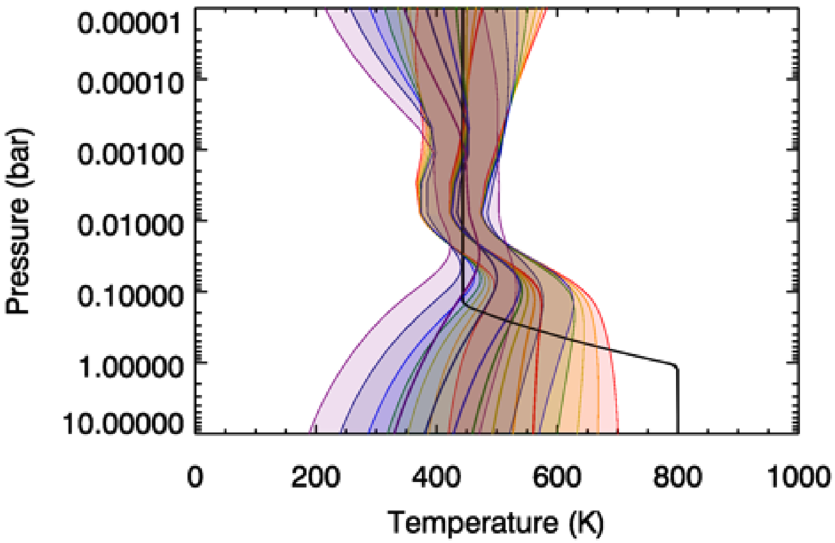

Figure 8: Retrievals of the dayside temperature profile from 30x synthetic noisy eclipse spectra of GJ 1214b. The different colours correspond to different priors used in the retrieval; the retrieval is sensitive to atmospheric temperature in the region where they converge. The true temperature profile is shown in black. The thick lines indicate the retrieved values and the thin lines/shading indicate the error on the retrieval.

5 SUMMARY

Barstow et al. (2013) find that, for the simple cases described in this document, observations with EChO could be used to constrain the structure and composition of warm and hot Jovian atmospheres. Further investigation must be undertaken to investigate the effect of scattering clouds and hazes, and atmospheres with unknown mean molecular weights, on this process, but the results of Barstow et al. (2013b) for GJ 1214b indicate that EChO will represent a significant advance over currently best-available techniques and observatories. EChO represents the only current prospect of simultaneously acquiring spectra from the visible to mid-infrared, which will be crucial for breaking degeneracies and fully exploring the exoplanet parameter space. EChO's faintest/brightest target requirements are sufficient to allow the observation of the planets listed in this document, covering the parameter space from Jupiter-sized objects to Super-Earths, and equilibrium temperatures ranging from 450 – 1500 K.

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