Characterization of the Atmosphere of Super-Earth 55 Cancri e using High Resolution Ground-Based Spectroscopy

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1 INTRODUCTION

With the recent surge in discoveries of exoplanets thanks to the Kepler and K2 missions, interesting exoplanets are being found in significant numbers. The class of exoplanets known as super-Earths consists of those with a mass greater than Earth but significantly lower than Neptune. To date, there are roughly 200 such exoplanets confirmed. While the literature regarding the atmospheric properties of hot Jupiters has been progressed significantly (e.g. Swain et al. 2009; Deming et al. 2013; Sing et al. 2016), the available information for super Earths is limited due to the higher signal to noise ratio required. Furthermore, the number of super-Earths known to orbit bright stars that make for favourable conditions for characterizing atmospheres are few.

One such exoplanet, 55 Cnc e, is a very good candidate to study atmospheric properties. Discovered in 2004 (McArthur et al. 2004), it orbits a G8V star, a very bright star compared to other hosts of transiting planets, in just 18 hours, and has a mass of approximately 8 Earth masses (Winn et al. 2011; Demory et al. 2011). With a mean density comparable to that of Earth's and a high mass that suggests an interior with greater compression, it is inferred that the planet has an envelope with a significant mass of lighter elements and compounds. The mass-radius relationships of such planets have been investigated by Winn et al. (2011); Demory et al. (2011); Gillon et al. (2012), and the two explanations of the mean density of 55 Cnc e are that it either has a low-mass atmosphere consisting mostly of hydrogen and helium, or it has a high-mass, water-dominated atmosphere. However, the first explanation is unlikely due to the short evaporation timescale of hydrogen and helium of order a million years (Valencia et al. 2010).

This led to an investigation (Esteves et al. 2017, hereafter E+17) to place constraints on the presence of water in the atmosphere. Their results are compatible with either a cloudy atmosphere (in which constraints cannot be placed), or an optically thin atmosphere which is either lightweight and depleted of water, or heavy and includes water. In the case where the atmosphere is water-rich, they were able to place a lower bound of 10g/mol on the mean molecular weight. Although E+17 did not detect water, they demonstrated that it is possible to recover water-vapour signals in nearby super-Earths using ground-based instruments.

Since the analysis done by E+17, there have been four additional nights of observation. The data was collected using GRACES (the Gemini Remote Access to CFHT ESPaDOnS Spectrograph
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powerful ESPaDOnS (Echelle SpectroPolarimetric Device for the Observation of Stars) spectrograph at the CFHT (Canada France Hawaii Telescope) to which the data is fed using a fiber optic feed. The exposure time used was 40-60 seconds per frame. This data is very high resolution and provides the signal to noise needed to perform this investigation. A summary of the observing nights is displayed in Table 1.

In this investigation, I will improve on the result of E+17 by performing a similar analysis with this additional data. With four more nights of high resolution data, it is likely that water in certain possible atmospheres for 55Cnc e will be detected if it exists, or significantly more models can be ruled out. In the best case scenario, we will be the first to detect water on a super-Earth, marking a crucial advancement in the progress of exoplanetary science and providing a deeper understanding of the prospects of habitability in the universe.

Night #	Date (UT)	Frames	Duration (h:m)	Mean SNR
1	Nov. 22, 2016	80	2:32	281
2	Dec. 23, 2016	155	4:00	388
3	Dec. 26, 2016	125	3:59	192
4	Jan. 3, 2017	158	4:06	461

Table 1. This table summarizes the four nights of observations (each of roughly 4 hours except the first) taken by GRACES.

2 PROPOSAL

The analysis of the data collected from GRACES will be performed in a similar manner as the analysis done in E+17. The data collected is flux as a function of wavelength, for several orders of wavelength, and taken at multiple times (frames) during the night for each night. This raw data has large-scale time-dependent variations. To remove this, I will perform a process called blaze correction. This involves picking one frame (roughly the middle one) to serve as a reference frame. For each frame, I divide it by the reference frame and fit a low order polynomial to the quotient. I then divide the given frame by this polynomial, and repeat for every frame. During this process, I remove outliers that may arise in the reference frame (eg. cosmic rays), by defining a threshold multiple of median absolute deviations.

Next, any additional systematic time-dependent variations must be removed. This can be done using a detrending algorithm described by Tamuz et al. (2005), as done in E+17. This algorithm removes such variations by finding coefficients of time-dependent functions that appear at several wavelengths and dividing them out. Each order will be treated separately, and several iterations of this algorithm will be applied to remove different systematic effects. One example of such an effect is the fact that as the telescope tracks the object as it moves across the sky, it observes through a varying amount of atmosphere. The signal from 55 Cnc e's atmosphere will remain, due to its rapid change in radial orbital velocity during the observing night.

After this, a Doppler cross-correlation technique will be used to disentangle the lines due to 55 Cnc e's atmosphere and those of the Earth and the host star and detect water. In order to employ this method, E+17 used a model that was calculated specifically for 55 Cnc e using molecular data from the high-temperature molecular spectroscopic database (HITEMP) as described by Rothman et al. (2010). Such models are calculated using a grid of atmospheric volume mixing ratios and mean molecular weights. The models are then convolved to match the resolution of whichever data they will be used with. Each spectrum will then be correlated with these models at various values of Doppler shift. The strength of the correlation with the model will then be measured.

The last step of the analysis involved will include model injection and recovery tests. To estimate the significance of a detection, the models can be injected into the data by simply multiplying the in-transit spectra by the atmospheric model. By injecting a water signal of varying strength, and determining which can be recovered by this analysis, limits will be placed on the results. For example, in E+17, for water-rich atmospheres (volume mixing ratios of > 10%), it was found that models with mean molecular weights of below 10g/mol should have appeared as a 3σ detection in the data.

With access to additional data, it is anticipated that the constraints on the atmosphere of 55 Cnc e will be significantly improved, with water likely being detected.

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