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Exoplanets – Analysis Project 2

Transit Spectrum Tier 3 – Write-Up

I. Abstract

We are tasked here with using a transit spectrum, as well as opacity information for H_2O and CH_4, to retrieve information about the atmospheric pressure scale height, atmospheric temperature, and the log (base 10) of the water vapor and methane volume mixing ratios for an exoplanet. The given data ranges a 0.4-1.7 micron wavelength range. The retrieval of these four parameters was executed using a Markov Chain Monte Carlo (MCMC) method. After defining some prior constraints, I was able to determine the most likely range for these parameters using python's *emcee* function. The results were H = $69.31^{+4.87}_{-4.74}$ (km), T = $635.1^{+185.5}_{-159.4}$ (K), log(fH_2O) = $-4.145^{+0.151}_{-0.155}$ and log(CH_4) = $-4.607^{+0.178}_{-0.173}$. After receiving these results, I also derived the C/O ratio for the atmosphere. This was accomplished by dividing the methane fraction by the water fraction (or methane mixing ratio by the water mixing ratio, derived using *emcee*). The result was the C/O ratio is ~$0.34^{+0.19}_{-0.12}$.

II. Approach and Methods

Going into this project, we have some background information available to us. The first is a transit spectrum over the 0.4-1.7 micron wavelength range, along with the associated uncertainty on the spectrum. Additionally, we know the opacity information for H_2O and CH_4 over this wavelength range. Using this information, the end goal is to retrieve some information about the planet, including scale height (H), temperature (T), the water and methane mixing ratios, and the C/O ratio of the atmosphere.

We can use transit spectra to learn things about exoplanets. Do they have dense atmospheres? Are they airless bodies? If they have atmospheres, what sorts of species do they contain? This information can be revealed by absorption features in the spectra. For this reason, I first plotted up the raw data (Figure 1) out of curiosity. We can see that there is definitely some behavior in the transit spectrum. Specifically, we can see spikes suggesting that we aren't looking at an airless body. This checks out, as our prior data indicated there would at least be a presence of H_2O and CH_4.

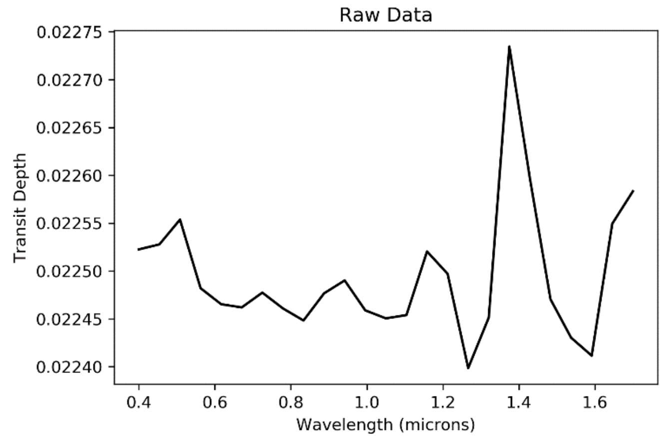

Figure 1: Raw data, where x-axis is wavelength, in microns, and y-axis is transit depth.

Some other assumptions that can be made are that the stellar radius is 0.78 R_{sun}, there is a planetary 10-bar radius of 1.16 $R_{Jupiter}$, an H_2 volume mixing ratio of 0.85, and a He volume mixing ratio of 0.15. This is also based on prior knowledge that we know about the system.

The bulk of this project revolves around a forward model, which the *emcee* function needs to fit transit depths to. Prior to creating this forward model, my first step was to define a pressure grid for the planet. This extends from the planet's 10-bar radius, to the top of the atmosphere. Once this was defined, I could start to work inside of my forward model. First, I calculated an altitude grid using the hydrostatic equation: z = H*log(p0/p), where H is the scale height *emcee* is fitting for, p0 is the surface pressure and p is our pressure grid. From there, I calculated the height across an atmospheric layer of our pressure grid, and a number density profile along the pressure grid. These were ultimately used to compute optical depth across a layer. The optical depth across a layer was the trickier part of the forward model. This simply being because we had to account for things like Rayleigh scattering of H_2 and He molecules, as well as the collision induced cross-section of H_2. Luckily, we have prior functions given to calculate this for us. So, I determined the total optical depth across a layer by adding optical depth of water vapor, optical depth of methane, optical depth when factoring in Rayleigh scattering, and the fourth opacity source, from collision-induced absorption.

Another function we are given is the transit_depth function. This function takes as inputs: planetary radius, stellar radius, our grid of altitudes, and the layer vertical optical depth matrix. It then outputs the modeled transit depth (which my forward model ultimately outputs). From here, I defined a log-likelihood function, which takes as inputs the four parameters we're looking for (H, T, fH_2O, and fCH_4), and our given arrays for wavelength, transit depth, and transit depth error. Using the modeled transit depth from the forward model, as well as the data for transit depth, it outputs a log-likelihood. Additionally, I defined a log prior function, which takes as inputs the four parameters we're looking for (H, T, fH_2O, and fCH_4). The log prior function puts reasonable constraints on the fitted parameters. Some bounds I used were: $0<T<3000$ K, scale height must be positive, $-10< fH_2O<0$ and $-8<fCH_4<0$. The constraints on the volume mixing ratios were determined after observing runs of *emcee*, and seeing where the data seemed to want to congregate. Finally, I implemented Bayes theorem, by combining the prior constraints with the log-likelihood.

After creating these functions, I was able to define a starting point for my walkers (H=200km, T=1500K, $\log(fH_2O)=\log(fCH_4)=-4$), and run *emcee*. My results follow.

III. Results

When I first ran *emcee*, I used less walkers, a lower burn and a lower number of steps, to check to make sure things were running smoothly. Once I felt like my code was strong and errorfree, I ultimately used the following: **number of walkers: 100, number of steps: 1000, and burn-in period: 400**. Using this resulted in Figure 2:

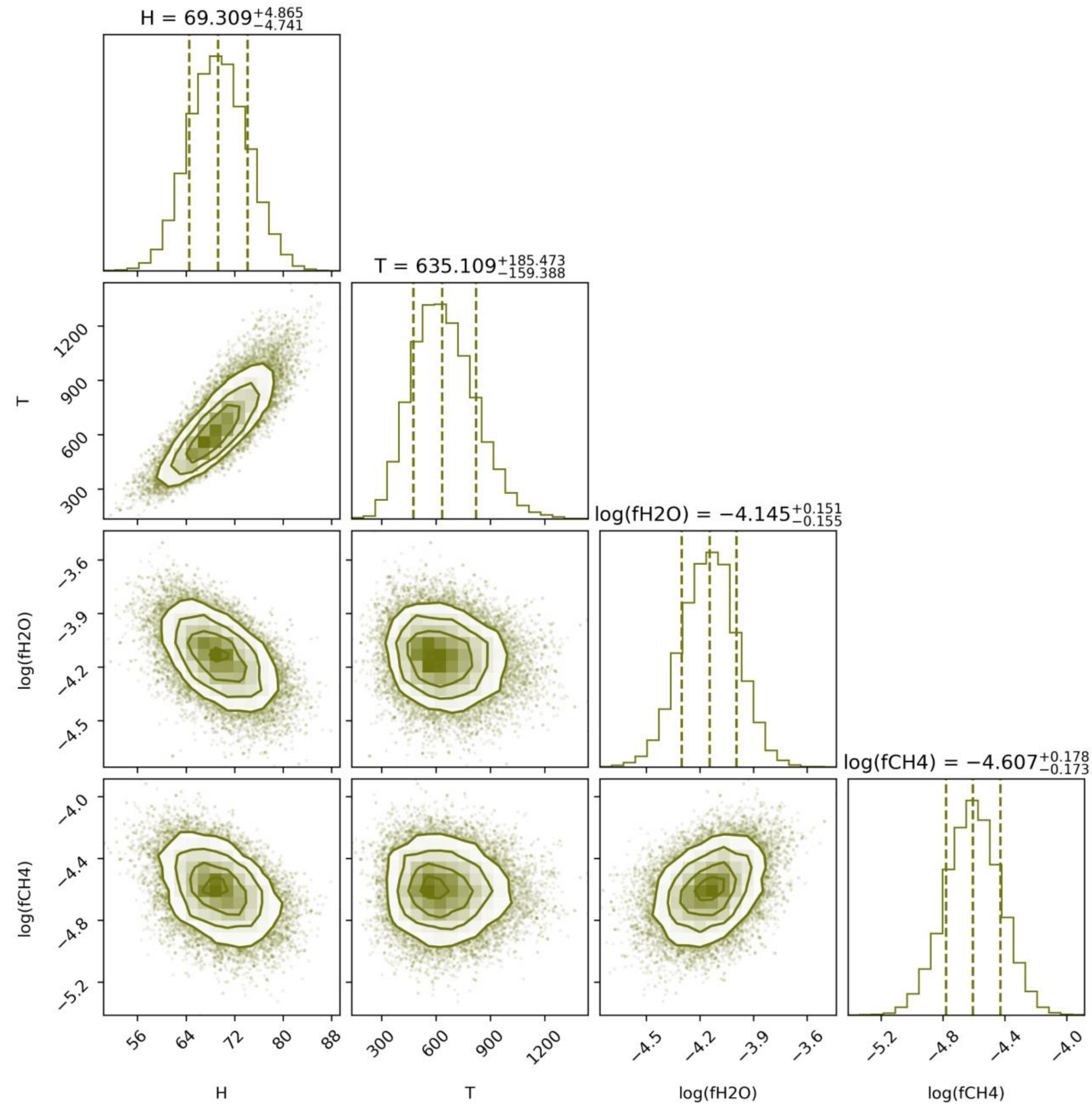

Figure 2: Triangle/ corners plot for scale height, temperature, and the log forms of the water and methane volume mixing ratios.

This results in the following:

H (km)	T (K)	log(fH2O)	log(fCH4)
$69.31^{+4.87}_{-4.74}$	$635.1^{+185.5}_{-159.4}$	$-4.145^{+0.151}_{-0.155}$	$-4.607^{+0.178}_{-0.173}$

From here, I derived the C/O ratio for the atmosphere, by dividing the methane fraction by the water fraction of the atmosphere. The result was the C/O ratio is ~$0.34^{+0.19}_{-0.12}$. The 1D marginal distribution of these results is displayed on the right in Figure 3.

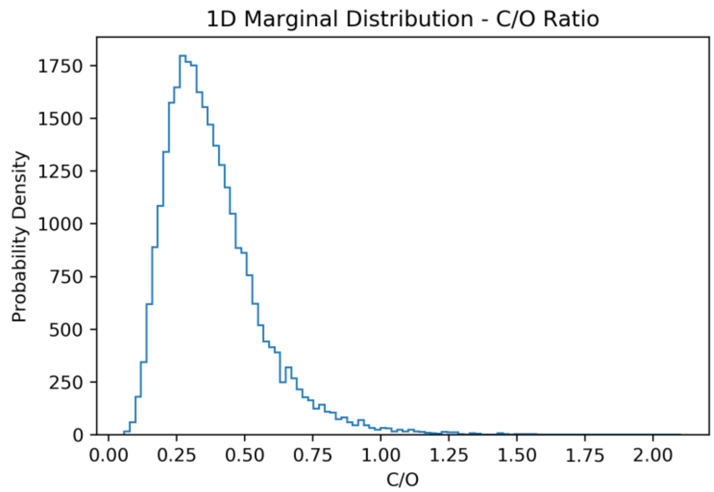

Figure 3: Histogram of 1D Marginal Distribution for the C/O ratio of the atmosphere.

IV. Discussion

These results suggest that this is a pretty hot planet. For reference, the atmospheric temperature of Jupiter is ~100 K. Perhaps the planet we are looking at is a hot Jupiter, as 600 K might be unlikely for a rocky planet, unless it possesses an extremely thick atmosphere like Venus.

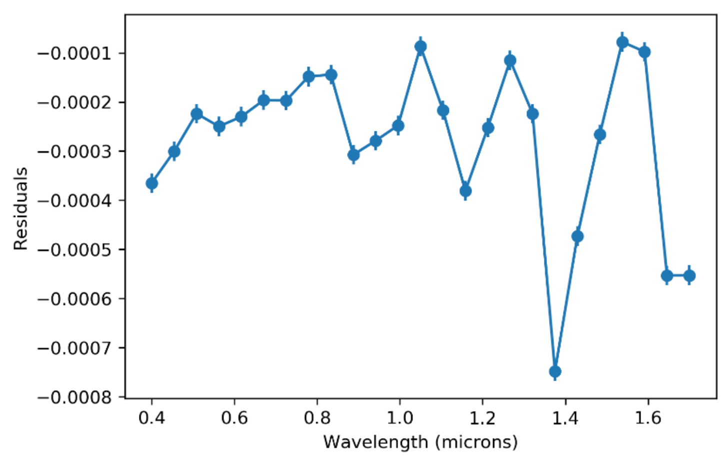

Figure 4: Residuals using model and data for transit depth.

Something I wanted to check was the residuals of the data. This results in Figure 4 on the right. It looks like there is a lot happening in the residuals, but if you look at the y-axis, you'll notice that these are very small data points, which is good and suggests a solid fit of model to data.

V. Conclusion

Overall, using python's *emcee* function, we are able to get a solid guess for the best-fit of scale height, temperature and the volume mixing ratios for methane and water vapor. This is an interesting result because we were able to determine all of this information using just the transit spectrum, and some opacity information. Transit spectroscopy provides a useful tool to exoplanetary research, and aids us in learning more about these planetary systems that reside very far away from us.