Modeling Observations of Exoplanets in the Mid-IR

Student- M.Autore, Mentor- M.Richter

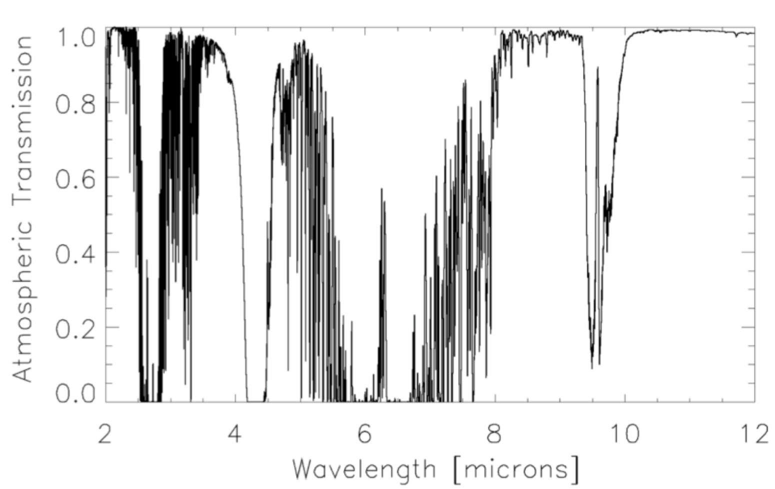
January 2, 2019

Abstract

The purpose of the project is to create a convenient and easy to use tool for modeling and analyzing planetary spectra. The function of such a tool would help communicate the quality and limitations of observations made by a space-based spectrograph implemented to characterize exoplanets and interstellar medium. This tool combines NASA's Planetary Spectrum Generator (PSG) and the HITRAN API (HAPI), two very powerful resources in spectral analysis, in a Python package for simple and timely analysis. The modeling tool was built with the intention of generating realistic observations, however it has viability to be a power spectral analyzer with the utility of HAPI.

1. Purpose and Theory

Spectroscopy is the standard means to probe unknown chemical systems, providing a more intimate understanding of the identity and abundance of their compositions. In this golden era of exoplanet exploration, spectroscopic methods are the best way to collect chemical information of these new worlds. Several observational methods already exist in astronomy, but it is an irrefutable fact that space-based observations are the superior form due to the absence of telluric background signals (figure 1); however, space-based observations are the most expensive and time consuming to execute. Having a toolset for which one can predict the results of observation is powerful and instrumental to the process leading up to launching a spectrograph into space. A seemingly insurmountable task in this proposal processes is convincing others that the results given by such an instrument will be worth the resources necessary to achieve it. For the purpose of exoplanet characterization, a spectrograph would need an unprecedented spectral resolution and be created for infrared observation.



[Figure 1] The telluric background signal is the spectrum originating from Earth's atmosphere. This figure shows the telluric background signal that appears in ground based observations of the mid-IR.[5] In this region of the electromagnetic spectrum there are many features which distract from the object being observed. The figure demonstrates that there are virtually no wavelengths in this region that reach Earth's surface without some attenuation.

The importance of observing in the infrared is due to infrared radiation's permeability through the interstellar medium (ISM). Radiation of this wavelength is associated with vibrational energies of dipoles, and, due to the ISM's composition being mostly hydrogen, this radiation permeates without being absorbed. This has the significance that the collected light is highly characterized by its source. A myriad of molecules having great significance across many disciplines in space exploration possess spectral features that display in the infrared. Molecules belonging to the class of amino acids, or water even, have distinct and prominent absorption/emission peaks in the infrared. If a spectrograph had the resolution to detect these in exoplanet atmospheres or protoplanetary disks, then it would aid in the search for life elsewhere in the universe. This is just one application of such an instrument and the necessity of observing celestial objects in the infrared.

With the nature of observing chemically rich environments, a high resolution is needed to sort out the messy conglomerate of spectral features considering that only the infrared section is desired. Without high resolution, too much chemical information would be indiscernible and investment of resources for such an instrument would be short sited. Not to mention the higher resolution should also help increase the signal to noise ratio, allowing for easier separation of the data from any noise from the background or instrument.

The purpose of this project is to create a tool that allows for the input of instrumental parameters, mimic real-life measurements, and data analysis. The last feature ensures long term viability for the tool as it could later be modified for more in-depth analysis of real data. The tool will be designed to show and communicate the usefulness and impact that a spaced-based high resolution telescope could offer in characterizing atmospheres of exoplanets, star and planet formation regions, and potentially even the ISM. For data analysis, the tool will incorporate the HITRAN API (HAPI), a common resource for spectroscopic data analysis. Mock data that will be used in the tool comes from NASA's Planetary spectrum generator. The tool will combine the power of both resources into a convenient package.

2. Technical Background

This section describes the use and function of the planetary spectrum generator and HITRAN, packages used to create the modeling tool.

2.1. Planetary Spectrum Generator

NASA's Planetary Spectrum Generator (PSG) is versatile tool for creating unique planetary spectra and referencing real exoplanets with predefined planetary spectra. Even previously generated files can be uploaded to update and edit previous queries. Parameters that can be edited to acquire a generated spectrum are the planetary target, viewing geometry, atmosphere: molecular abundances, aerosol scattering, surface properties, and instrument/telescope settings themselves. There also an option to select objects at defined UT date/time, where PSG will look through an ephemeris (position of astronomical objects in the sky at given time) and fill parameter fields from NASA's exoplanet database.

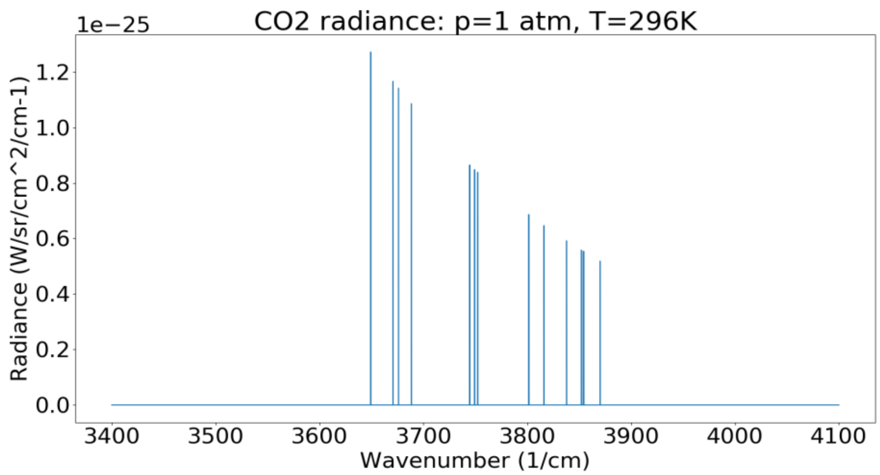
For the purpose of this project, the parameters were entered in manually to create an idealized scenario for a planet similar to Proxima Centauri b. Assumptions made to generate the spectrum were a constant temperature throughout the atmosphere, a stratified atmosphere, as well as a significant fraction of the atmospheric being comprised of water.

PSG has an option to add noise to the spectrum, however this feature was not implemented at this time. It is intended that in future work this will be added to generate a more authentic observation. Adding the noise currently adds a challenge for the project that is unessential for the overall goal. The spectrum product should have little to no noise anyways, therefore adding this feature is unessential to the functionality of the tool at this time. This feature will be added in the future to enhance the data analysis viability once there is real data to characterize so that there will be a method for the noise to be taken out.

2.2. HITRAN API

The HITRAN API (HAPI) allows for line-by-line data from the HITRAN*online* site to be downloaded to a local machine. It is built of conventional Python structures (lists, tuples, and dictionaries) for representing spectroscopic data. It allows for the powerful utility of HITRAN*online* to be directly used on data being worked on in a Python environment. Some useful spectral functions that can be calculated with this tool: absorption coefficient, absorption spectrum, transmittance spectrum, and radiance spectrum.

There is a particular interest in the spectral templates for specific molecules that HAPI can overlay onto real, or mock, data sets. This allows for the quick identification of chemical peaks in an observed spectrum. Figure 2 shows such a template for carbon dioxide at standard conditions created by HAPI. This template can be stacked on a given spectrum and analyzed to see if the template peaks appear in the observation.

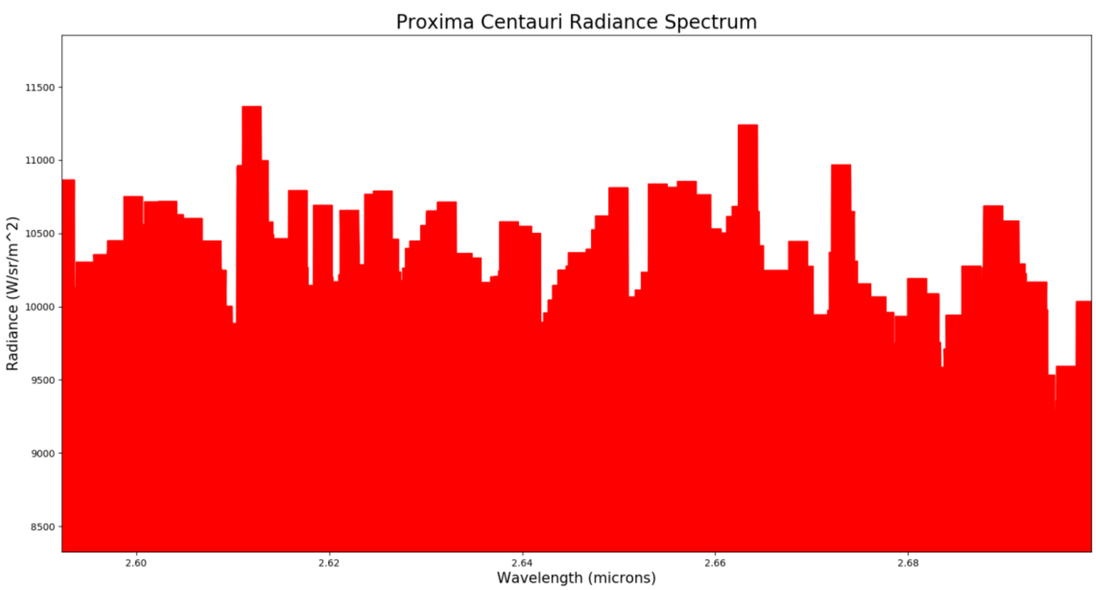


[Figure 2] Shows the HAPI template for Carbon Dioxide under standard conditions.

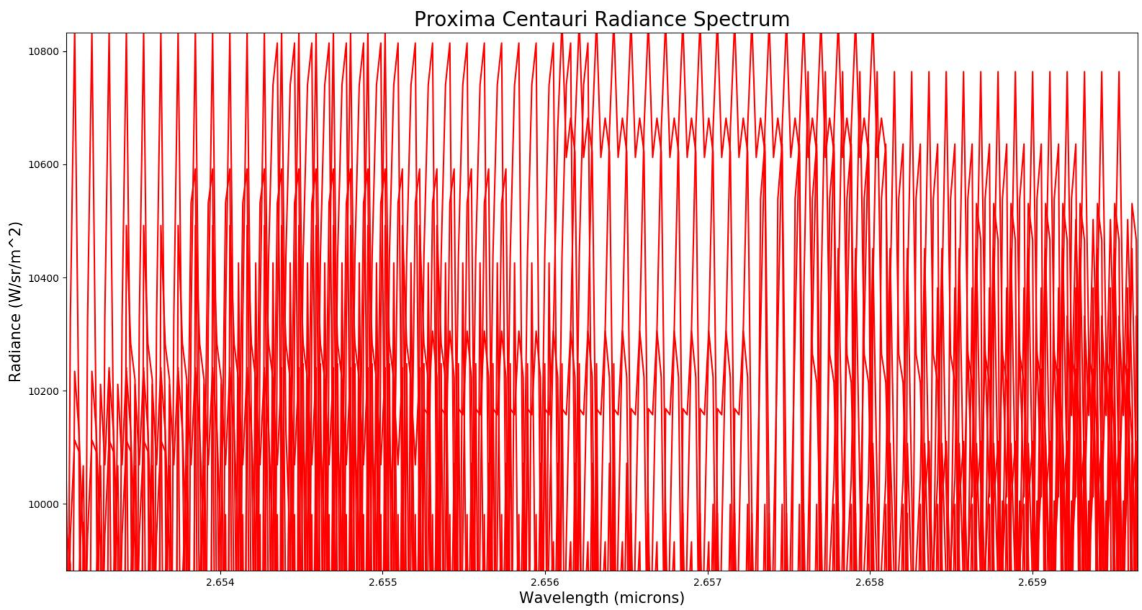
2.3. Modeling Tool

With files from PSG downloaded, the tool takes the data file and separates the contents within. There are different spectral measurements that the file contains including, but not limited to, contrast and spectral radiance across different wavelengths in the mid infrared. The tool can store many different data types at once, where the user can then choose what fits their analytical needs. At this point the spectra includes both the signal from the host star (Proxima Centauri) and the exoplanet of interest (Proxima Centauri b). The tool sifts through datafiles generated by PSG that match the inquiry the user enters. For example, the user may query for spectral radiance data between 2 and 4 microns and the tool will only pull data that matches that specification from the user. Once data is selected, further grooming is done that mimics realistic observations.

Optimal use of the tool, although not necessary depending on the object of interest, includes insertion of orbital parameters. This is another reason why Proxima Centauri b was chosen. This exoplanet has been well studied with many characteristic parameters already known such as radial velocity, eccentricity of orbit, and mass. Since the celestial object is moving the tool creates the expected Doppler shift based off the orbital parameters entered as well as the length of the observation. This essentially creates a smear of the raw spectrum downloaded from PSG and is analogous to an observation one might makes of a transiting exoplanet. The tool asks for the resolution of the instrument being used, the wavelength range of interest, period of the body (if applicable), stellar period (if applicable), radial velocity, semi-major axis of orbit, eccentricity, periapsis stellar longitude, mass of the planet and star, and phase range the planet traverses during observation. With the above known the tool can then create the appropriate doppler shifts based from where the planet begins to be observed and when the observation ends. The tool starts by constructing the geometry of the orbit, finding values for radial length and integrating the area covered during the planet's orbit. This, along with the planets period, can be used to find the area the planet sweeps per second in its orbit. This is then used to find the change in phase per time which can be easily be converted to radial velocity. This process allows for the creation of a table relating radial velocity to a phase angle, which for Proxima Centauri b is between 0 and 15 km/sec. With this table, the planetary spectrum can be appropriately red or blue shifted, based off the parameters entered (phase range) into the tool. A similar process creates the Doppler shift for the star orbiting its barycenter. Figure 3 and figure 4 represents a visualization of a shifted spectrum.



[Figure 3] Shows the Doppler shifted stellar spectrum. At first glance it looks as if it were at low resolution, but the block-like peaks are a result from the smearing of the spectrum. The spectrum is smeared due to the object's change in radial velocity along the observational line of sight.



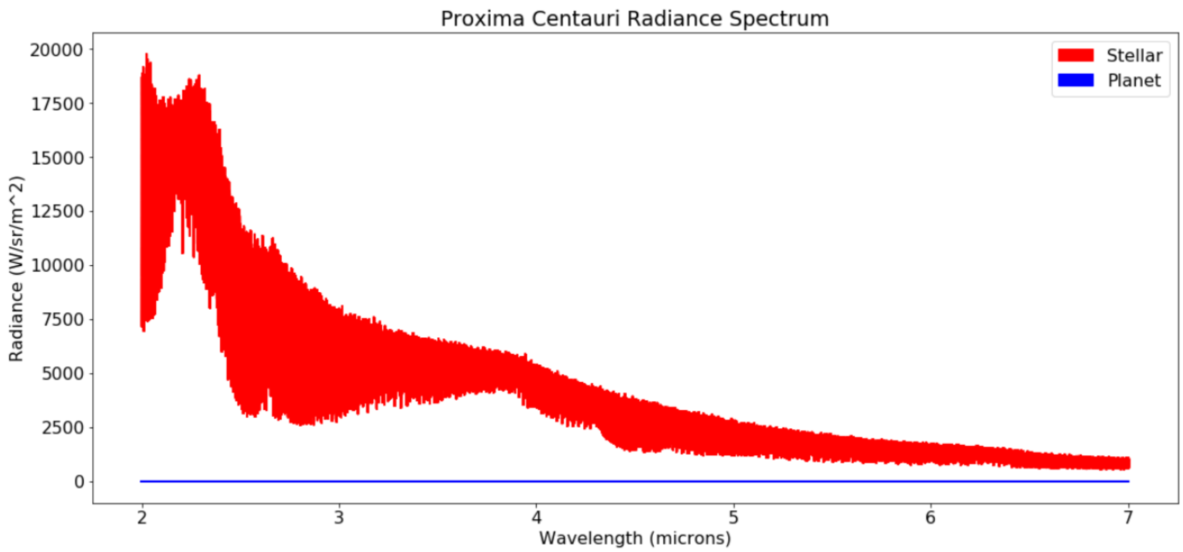
[Figure 4] Shows a closer examination of the stellar spectrum. At this level it is easier to see how the peaks are being shifted around.

In realistic observation, the stellar spectrum is an unwelcomed visitor that needs to be removed. With our mock observation the stellar spectrum is eliminated by stacking all the shifted stellar spectra, taking the median spectrum, and subtracting it from the data across all wavelengths. This leaves behind only the planetary spectrum. Again, the isolated spectrum is stacked with the median taken to reveal the unshifted planetary spectrum. This is the final product, a spectrum containing characteristic features of molecules in the planetary atmosphere.

3. Results

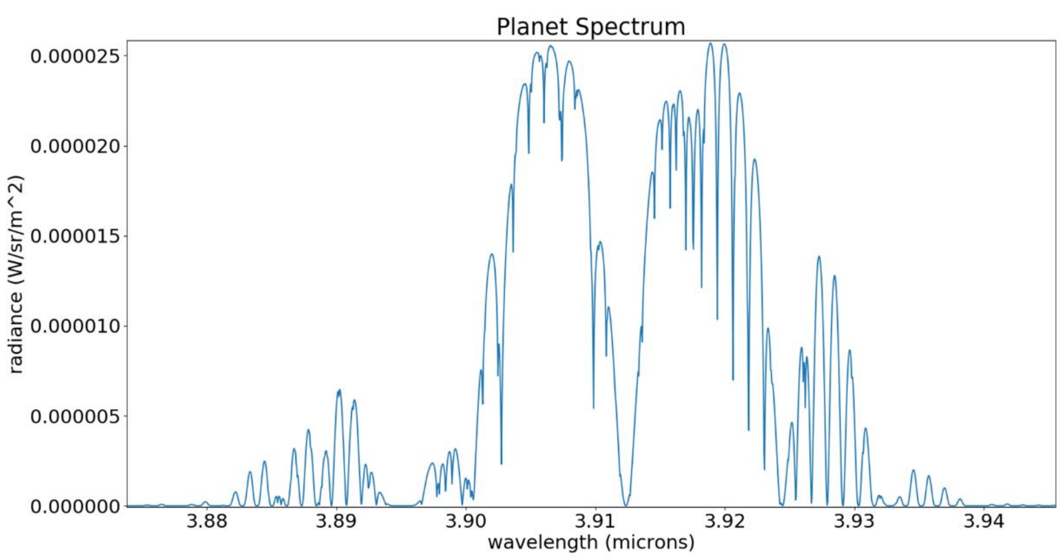
The results are that of an instrument pointing at an exoplanet similar to that of Proxima Centauri b with 50,000 resolving power. The spectra shown in figures 5 and 6 are in the mid-infrared between 2 and 7 microns.

Figure 5 represents the spectrum of both Proxima Centauri and Proxima Centauri b before doppler shifts are taken out. As expected, the stellar spectrum washes out the planetary. This is shown in figure 5 where the planetary spectrum appears as a constant line when compared to the stellar spectrum. Therefore, the stellar spectrum needs to be subtracted out of the data to isolate the planetary spectrum



[Figure 5] Shows both the stellar spectrum (red) as well as the planetary spectrum (blue) as generated by the code.

Figure 6 shows the isolated planetary spectrum after the stellar spectrum has been subtracted out. This represents an idealized case where noise has not been added to the data. The signal here represents the spectral features of water. An analysis to find out which peaks align to emission by water is best suited by HAPI.



[Figure 6] Shows the isolated planetary spectrum.

With the planetary spectrum isolated, HAPI can be used to identify characteristics as well as quantities based off the signal peaks. I will refer the reader to the HAPI manual on how the data analysis works with all the features it offers, which can be found online.[2]

4. Conclusion

The tool successfully combines the power of NASA's planetary spectrum generator and HAPI. As long as there is a source for mock data, the tool can be used to predict what an instrument of given parameters can measure. Also, given real data the tool can be used for the HITRAN API functionality.

One thing that is missing is the noise in the mock data and by the instrument itself. The next step in this project would be to add noise and see if conventional means used by astronomers already can be added to the tool to increase the signal to noise ratio.

5. Reference

1. Villanueva, G. L., Smith, M. D., Protopapa, S., Faggi, S., Mandell, A. M., Planetary Spectrum Generator: an accurate online radiative transfer suite for atmospheres, comets, small bodies and exoplanets, Journal of Quantitative Spectroscopy and Radiative Transfer, submitted.

2. R.V. Kochanov, I.E. Gordon, L.S. Rothman, P. Wcislo, C. Hill, J.S. Wilzewski, HITRAN Application Programming Interface (HAPI): A comprehensive approach to working with spectroscopic data, J. Quant. Spectrosc. Radiat. Transfer 177, 15-30 (2016) DOI: 10.1016/j.jqsrt.2016.03.005

3. Carr, J. S. and Najita, J. R., “Organic Molecules and Water in the Planet Formation Region of Young Circumstellar Disks,” Science 319, 1504 (Mar. 2008).

4. Bitner, Martin & Richter, Matthew & Lacy, John & Nomura, Hideko & Greathouse, Thomas & Blake, Geoffrey. (2018). Resolving the Location of Protoplanetary Disk Gas in AB Aur.

5. “Allen's astrophysical quantities”, 4th ed. Publisher: New York: AIP Press; Springer, 2000. Editedy by Arthur N. Cox. ISBN: 0387987460