Performance Assessment of NASA Mission Proposal to Characterize Exoplanet Atmospheres with Space-based High-Resolution IR Spectrometer

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Abstract

The search for life beyond our Solar System requires the remote detection of molecules in exoplanet atmospheres. One goal of the James Webb Space Telescope (JWST) is to detect particular molecules in the atmospheres of transiting exoplanets with the help of longer wavelength coverage and improved sensitivity. Higher spectral resolution in the infrared region beyond that of JWST could reveal a greater wealth of information about key molecules in these atmospheres. We use of a model of HD 209458b's transmission and eclipse spectra to simulate observations for a proposed infrared spectrometer with ten times the resolution of JWST. The spectrometer would be launched into space and could make these measurements. We explore its parameters and noise tolerances in order to support a satellite mission containing the suggested infrared spectrometer. We show that even signal-to-noise ratios as low as 100 can lead to statistically-significant measurements of exoplanet atmospheres. This work serves as a preliminary set of guidelines that will be crucial for making robust observations of exoplanet atmospheres with a space-based high-resolution infrared spectrometer.

Introduction

Since the first discovery of an exoplanet, or a planet outside of our solar system, thousands more have been confirmed. NASA's Kepler Space Telescope has uncovered that there are more planets than stars in the galaxy. These exoplanets exhibit a wide diversity of atmospheric compositions that may be studied remotely through a variety of detection methods.

As an exoplanet planet orbits its host star, some starlight that reaches distant observers is reflected or transmitted through the planet's atmosphere, dependant upon the phase of its orbit and inclination. At infrared wavelengths, observers measure planetary emission from the atmosphere rather than reflected stellar light. By comparing the spectrum of the star-planet system during various phases, one can obtain a spectrum of the planet's atmosphere. The remote detection of molecules in exoplanet atmospheres may soon allow for the discovery of potential signs of life, such as biomarkers in the atmospheres of Earth analogues (Kaltenegger & Lin 2021). Before this is possible, ground- and space-based telescopes must rely on infrared spectroscopy to identify an array of molecules.

Complications arise with observations of a star-planet system, since close-in planets are unable to be resolved separately from their host star. We therefore rely on High Resolution Spectroscopy (HRS) to help disentangle the exoplanet's spectrum from the overwhelming glare of their host stars. At high spectral resolution, molecular features are resolved into a forest of spectral lines that are unique to a given molecule. For planets closely orbiting their host star, the spectral lines undergo large Doppler-shifts, whereas the spectral lines of the host star remain essentially stationary. The planet's high speeds thus enable a velocity separation of the planet.

Armed with the isolated spectrum, we compare with high resolution spectra from atmospheric modelling codes to detect molecular lines in the spectrum, a form of exoplanet atmospheric fingerprinting. HRS is sensitive to both transiting and non-transiting exoplanets, and can characterize each planet's atmosphere because of its sensitivity to the depth, shape, and position of the planet's spectral lines. These parameters are altered by the planet's atmospheric composition, structure, clouds, and dynamics, including day-to-night winds and atmospheric rotation period (Birkby 2018).

To make more precise measurements of exoplanet atmospheres, we propose the Germanium Immersion Grating Spectrograph (GIGS). GIGS is a high-spectral resolution (R=25,000-40,000), mid-IR (3-8μm) space-based instrument that emphasizes the study of gas-phase molecular features in exoplanet atmospheres (Richter et al. 2018). At high resolution, broad molecular bands are resolved into dense forest of tens to hundreds of individual lines in molecule-specific patterns. H_2O, CO_2, CO, CH_4 and N_2O most substantially block spectral regions in the 3-8μm range of the Earth's atmospheric transmission. This means that these common, important molecules for a planet's atmosphere are difficult to study from ground-based observatories. Richter et al. (2018) therefore propose a space-based spectrometer that would not be affected by these interfering telluric signals. Furthermore, noise can be greatly reduced in space by several orders of magnitude if the telescope optics are cooled, like with JWST.

The key optical element of the proposed instrument is a gold-coated Germanium immersion grating (GIG). In general, the spectral resolving power for a diffraction grating is given by

$$R = \frac{\lambda}{\Delta\lambda} \tag{1}$$

which scales with the optical path difference (OPD) in waves between light hitting the extreme ends of the grating. However, for an immersion grating, diffraction occurs inside a crystal and light wavelengths are effectively reduced in size by the index of refraction, n. The OPD within the crystal is thus n times larger than in vacuum and a smaller grating can provide a given resolution. Germanium has a large index with $n = 4$, resulting in a beam area 16 times smaller than for a conventional grating. A smaller grating requires a smaller aperture and would lead to a more cost-effective method of studying exoplanet atmospheres at high resolution. The entire proposed spectrometer would be about the size of a hiking boot box.

In this work, we first take simulated observations of the atmosphere of HD 209458b, a well studied hot Jupiter, kindly provided by Jason Dittman of University of Florida. We apply noise constraints on the observations to motivate a space-based high-resolution infrared spectrometer that will make observations of exoplanet atmospheric spectra. Finally, we discuss the implications of our work and future steps.

HD 209458b Atmospheric Model

We use cloud-free, high resolution (R = 80,000) atmospheric models of HD 209458b (Fig. 1), a well-studied hot Jupiter with six molecules already simultaneously detected in its atmosphere (Giacobbe et al. 2021). The model outputs are wavelength (Å), stellar flux (erg/s/cm^2/Å), total system flux (erg/s/cm^2/Å) with planet spectrum subtracted from either a transit (from the limb of the atmosphere) or an eclipse (day side spectrum). The stellar model is from the Pollux database, with the right stellar type for HD 209458. There is evidence for cloud-free atmospheres on some

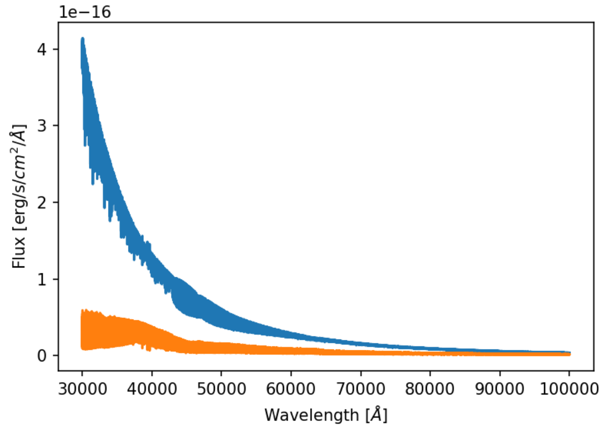


Fig. 1.—: Model cloud-free, high resolution (R = 80,000) atmospheric spectrum of HD 209458b, a transiting exoplanet. The blue signal corresponds to the transit case, where light from the host star is transmitted through the limb of the planetary atmosphere. The orange signal represents the day side spectrum of the atmosphere just before secondary eclipse.

hot Jupiters, so a cloud-free model remains largely reasonable.

Simulating Observations of Atmospheric Spectra

We use the aforementioned model of HD 209458b to simulate observations of spectra that would be observed by a space-based spectrograph, which would have unique access to important molecular transitions impossible to measure from Earth-based observatories. We work with the eclipse case, which has a weaker signal over all wavelengths, because it represents the worse of the two cases for later noise constraining and proves we can resolve molecular composition even with the worst signals.

In the case of a transiting planet, especially one with a short orbital period, the planet's light is Doppler-shifted to a much greater degree than its host star's as they orbit their common center of mass. The new observed wavelengths are found by:

$$\lambda_{\mathrm{obs}} = \lambda_{\mathrm{rest}} * \frac{\mathrm{v}_{\mathrm{rad}}}{\mathrm{c}} + \lambda_{\mathrm{rest}} \tag{2}$$

where λ_{obs} is the observed wavelength, λ_{rest} is the rest wavelength, $\mathrm{v}_{\mathrm{rad}}$ is the radial velocity, and c is the speed of light. We approximate the host star, HD 209458, to be stationary relative to the planet, since from orbital parameters the star has an orbital velocity of 95 m/s compared to the planet's orbital velocity of 150,000 m/s. Thus, for a given measured planetary signal, we would expect it to be at least partially Doppler-shifted compared to its model at rest unless at phases of 0° or 180°.

Since the pixels in GIGS measure fluxes at discrete wavelengths, and the signal from the planet is Doppler-shifted, we must bin the Doppler-shifted model wavelengths to the proper resolutions for each pixel. GIGS has two arms, red (5-8 µm) and blue (3-5 µm), with resolutions R = 25,000 and R = 40,000, respectively. In order to properly simulate observations by GIGS, we rebin the model data to these new resolutions, assuming equal bin spacing $\Delta\lambda$ by setting λ to the value in the

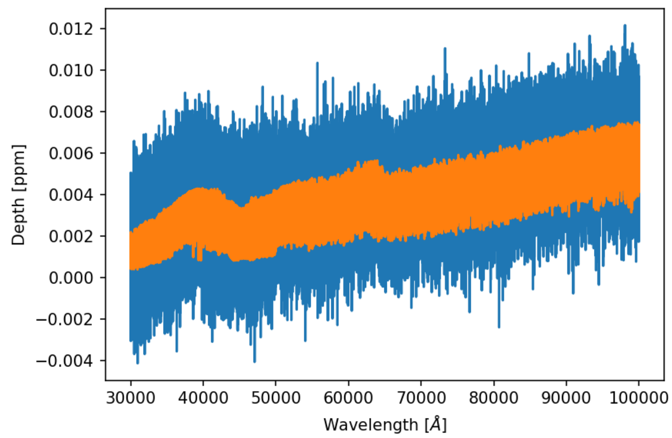


Fig. 2.—: Model and simulated observation of eclipse planet signal depth in ppm for a radial velocity shift of 400 m/s and rebinned to GIGS resolution parameters with a SNR of 1000. The orange signal is the model, and the blue represents the newly simulated observations. Note that some shape is still preserved despite the noise.

center of each arm's bin.

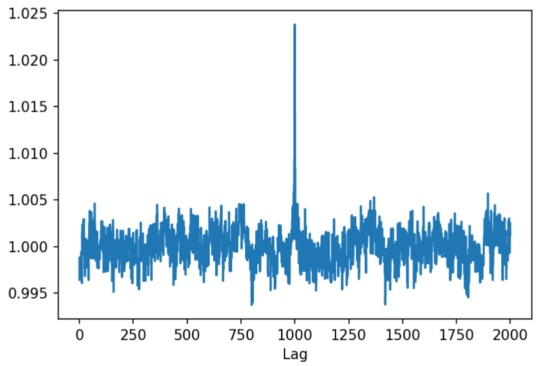
We hope to constrain noise for GIGS, so we work with signal-to-noise ratios (SNRs) of 100 and 1000 for the fluxes of both the star and the system (star - planet). We assume a Gaussian distribution of noise for both cases.

Finally, we subtract the noisy, Doppler-shifted star from the noisy, Doppler-shifted system to isolate the simulated planet spectrum. We then divide by the star to find the depth in parts per million (ppm). This results in a planet signal as shown in Figure 2.

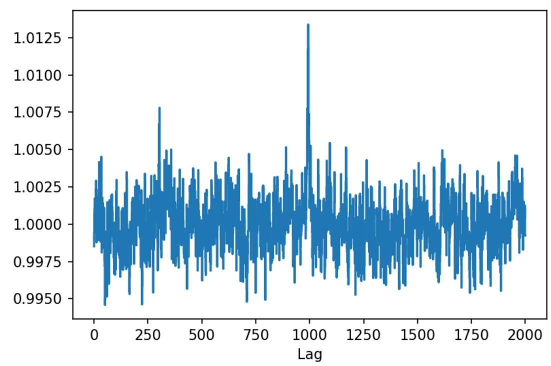
GIGS Noise Constraints

To constrain the significance levels for similarity between the noisy, Doppler-shifted planet signal and the model planet signal, we cross correlate the two signals. The amplitude of a cross-correlation signal is a measure of how well the two signals resemble one another, and the lag specifies at which location the two signals match best as one signal is stepped in front of the other. Lag for one pixel on the spectrograph corresponds to a velocity lag of 400 m/s, so a lag of 1000 is the same as a 0 m/s radial velocity shift and a lag of 1001 is the same as a 400 m/s shift. The cross correlations are normalized to best isolate the peak for each radial velocity.

Figure 3 gives us an optimistic constraint on the the noise allowable while still making high-significance measurements of molecules with models. The SNR is 100 for both radial velocities, with peaks of significance much greater than the 3σ usually required to make a statistically-significant discovery. Even for a non-trivial radial velocity of 24 km/s, we find a significance of over 7σ. These findings potentially require further study to more concretely confirm, but should stand as initial groundwork to support the observations GIGS would be able to make despite noisy conditions.



(a) Normalized cross correlation for radial velocity of 400 m/s and SNR of 100. Lag is 1000 and the significance of the peak is 14.05σ. Lag of 1000 corresponds to no shift in simulated observation and model signal for best fit.



(b) Normalized cross correlation for radial velocity of 24 km/s and SNR of 100. Lag is 993 and the significance of the peak is 7.88σ. Lag of 993 corresponds to a shift of 7 pixels for the simulated observation compared to the model signal for best fit.

Fig. 3.—: Normalized cross correlation of stationary model planet signal and noisy, Doppler-shifted planet signal for two arbitrarily-selected radial velocities, 400 m/s and 24 km/s. Lag for one pixel corresponds to a velocity lag of 400 m/s, so lag = 1000 is the same as a 0 m/s shift and lag = 1001 is the same as a 400 m/s shift.

Conclusions

In this paper, we used an atmospheric model of HD 209458b to explore a SNR of 100 for a proposed satellite mission to study exoplanet atmospheres with a Germanium immersion grating (GIG). We applied a normalized cross correlation to model planet data and the simulated observation from the designed spectrograph. This approach further motivates the utility of such a satellite to make robust observations of exoplanet atmospheres.

To build upon this work, we first suggest cross correlating many more times and for other SNR values to garner a larger sample of peak significances and lags to get a better statistical understanding of GIGS functionality. We would also like to work with other atmospheric models that better represent exoplanet populations. Finally, we would like to explore how well GIGS could measure the atmospheres of Earth analogs, which may harbor biomarkers resulting from life.

This work was supported by the University of California, Davis REU Program and National Sciences Foundation (NSF). Thanks to Jason Dittmann for the atmospheric model that made this project possible.

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