Draft version September 26, 2021
Typeset using LaTeX **twocolumn** style in AASTeX631

Non-Detection of Helium in the Upper Atmosphere of the Hot Jupiter WASP-44b

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ABSTRACT

We present a search for helium in the exosphere of a transiting exoplanet. WASP-44b provides us with the opportunity to probe the chemical composition of a hot Jupiter on a short orbit around a G8 type star in the constellation Cetus (Charbonneau et al. 2002). The NIRSPEC near-infrared spectrograph on the Keck II telescope at Mauna Kea Observatory, Hawai'i measured the transmission spectrum of the transiting exoplanet WASP-44b. We used the NIRSPEC Data Reduction Pipeline to reduce the raw data and extract 32 spectra of the WASP-44 system, taken over 3 hours. We used a model stellar spectrum to calibrate our data and obtained our final wavelength solution, showing a clear helium line in the stellar spectrum. We find that after comparing in transit and out of transit spectra that there is no significant increase in the transit depth at the 10830 Angstrom line. We find an upper limit on the excess absorption of 1 percent in the core of the helium line, which corresponds to a helium exosphere smaller than 1.25 planetary radii.

1. INTRODUCTION

The study of exoplanets is a rapidly growing field, as the first planetary systems were discovered less than three decades ago. Since then, thousands of worlds outside our own Solar System have been confirmed, leading many to speculate about the composition of such planets. Knowledge of the atmospheres of these exoplanets can provide new insights into planet formation, stellar evolution, and the origin of life. The purpose of this project is to analyze observations of a single transiting exoplanet using the NIRSPEC near-infrared spectrograph on the Keck II telescope at Mauna Kea Observatory, Hawai'i, in order to characterize its atmosphere. The specific planet we observed is WASP-44b, a hot Jupiter on a short orbit around a G8 type star. It is generally accepted that hot Jupiter atmospheres are composed mostly of hydrogen and helium, which we will be attempting to detect by measuring wavelength-dependent changes in the amount of light blocked by WASP-44b as it passes in front of the host star. This technique is known as transmission spectroscopy and is used to determine atmospheric composition of planetary systems Seager & Sasselov (2000). The presence of elements such as sodium and helium can be inferred from a transmission spectrum, which is a measure of the amount of light that is blocked by an exoplanet atmosphere at various wavelengths Öberg et al. (2011).

A detection of helium absorption during the transit would be significant, as it can reveal whether or not WASP-44b is losing a fraction of its atmosphere to space Sing et al. (2015). The metastable helium absorption line is at 10830 Å and is useful for probing outflows as it only exists in the upper regions of planetary atmospheres, where high-energy stellar radiation is absorbed. The question of which planets keep their primordial atmospheres and which planets lose them is a crucial one for understanding the long-term evolution of exoplanetary systems. The project involved converting raw spectra into a transmission spectrum using codes written in Python. Ideally, we would have been able to detect helium absorption in the extended atmosphere of WASP-44b. If the atmosphere is escaping, we could expect to observe blueshifted absorption. Figure 1 shows a transmission spectrum for a a previously observed exoplanet, WASP-107b in which the vertical dashed lines indicate the helium absorption triplet at 10830 Å and the red

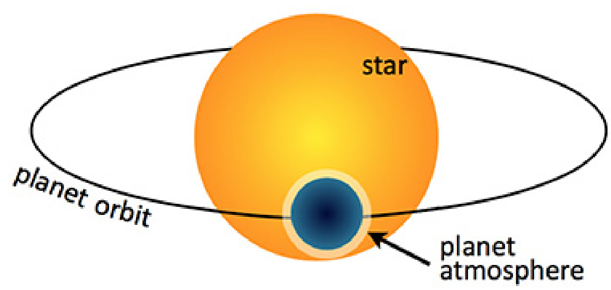

Figure 1. Cartoon of an exoplanet transit. Image credit: N. Nikolov

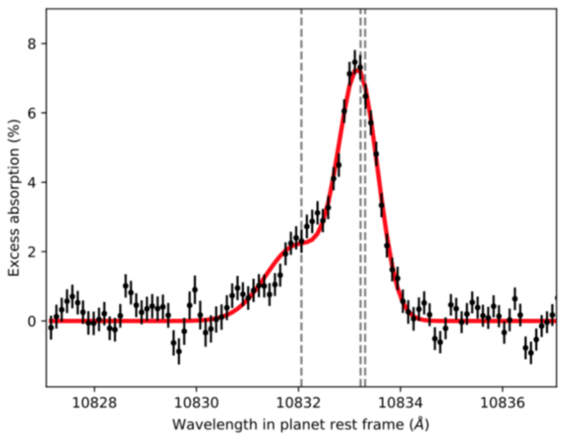

Figure 2. The excess absorption during a transit of WASP-107b in the planet's rest frame. Image credit: Kirk et al. (2020)

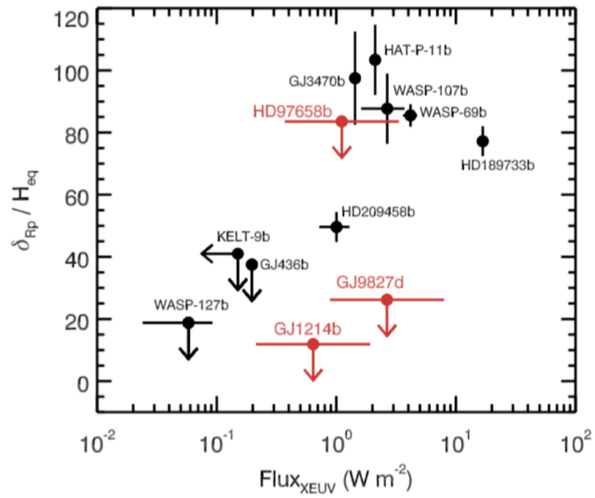

Figure 3. Previous helium detections. Image credit: Zhang et al. (2021)

line shows the fit of a double-peaked Gaussian. Our observations of WASP-44b were recorded with the same setup as WASP-107b shown in the figure.

There are currently only six exoplanets with published helium observations, as shown in Figure 2. The x-axis gives the amount of XUV flux received by the planet while the y-axis gives the size of the helium absorption signal normalized by the planet's atmospheric scale height. Points with arrows correspond to upper-limits from non-detections. Currently, there are no obvious correlations between the magnitude of the helium detection and other relevant system parameters, such as the XUV+EUV flux received by the planet. Other relevant parameters to consider include planet mass, stellar winds, and magnetic fields. Our observation of WASP-44b will add to this small data collection, helping to reveal potential population-level trends. Published theoretical studies of helium absorption suggest that stellar spectral type is important for setting the fraction of helium in the metastable state Oklopčić (2019). While WASP-44b orbits a G8 type star, only one of the six planets with a helium detection, HD209458b, orbits a G type star. GJ3470b orbits an M type star and the remaining exoplanets orbit K type stars. Such comparisons will allow us to explore how stellar type affects the absorption signal. Although we know from its mass and radius that WASP-44b is a gas giant planet with a massive hydrogen- and helium-rich envelope, there are currently no detections of absorption from WASP-44b's atmosphere in the published literature.

2. METHODS

Our general approach can be described as follows: Fix our science, flat and dark images by rotating and correcting for bad pixels with a custom code written in Python. The following step is to create the master flat image with our code and finally run the NIRSPEC Data Reduction Pipeline (NSDRP) software on our corrected raw data. Figure 4 demonstrates how the correction of images is implemented. Bad pixels can be caused by cosmic rays and detector cosmetics. The master flat image is created by taking the median of all corrected flat field images.

The central tasks of the NSDRP are to locate and extract individual spectral orders from object frames and flats, rectify orders in the spatial and spectral dimensions, and find a global wavelength calibration solution (Cohen et al. 2017). The pipeline imports flat fields and a pair of corrected FITS images called 'A' and 'B' and returns a series of reduced data products. The ABBA nodding pattern moves the target up and down the slit, which prevents A and B from overlapping. By taking the pair of images and subtracting one from the other, the pipeline is able to remove the background sky image and OH emission lines that appear in the spectrum due to the Earth's atmosphere. NSDRP performs dark subtraction on the flat field images and then proceeds to divide the 'AB' FITS image pair by the resulting flat filed image. After flat fielding, the pipeline modifies each spectral order independently by removing curvature of the order and slit tilt. Then it sums pixels across the regions that contain the target, producing spectra. Finally, the pipeline will produce a wavelength solution for each spectral order. The software results in a 2D image, profile, spectrum, and uncertainty for each order Muirhead et al. (2020). Once the pipeline has finished running, data products are generated from the reduc-

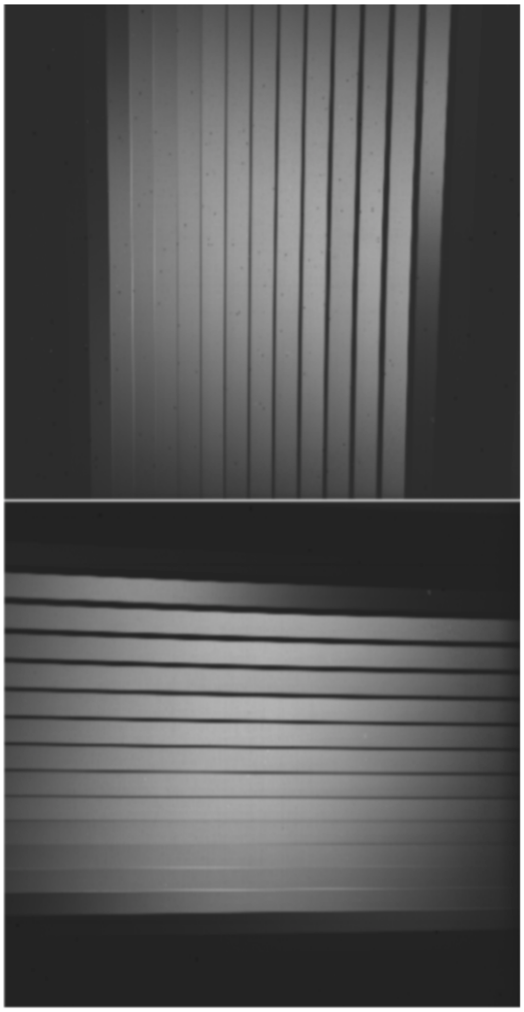

Figure 4. Top panel: Flat field image before correction. Bottom panel: Flat field image after correction.

tion results including ASCII tables, binary FITS tables, FITS images and various preview plots. With the results of the pipeline, we can go on to create a final wavelength solution by using a model stellar spectrum to calibrate our data. In order to determine the solution in 1D, we used a phoenix model with an effective temperature of 5240 K, surface gravity (log g) of 4.5 cgs, and metallicity of 0.0 to get as close to the parameters of WASP-44 as possible. Finally, we can compare the resulting spectra during transit and out-of-transit to obtain a plot that separates the amount of helium detected from the star and the planet. From these final results, we can search for helium absorption in WASP-44b's atmosphere.

3. DISCUSSION

Finally, we see a clear helium line at 10830 Angstroms in the stellar spectrum of WASP-44. This means that the star emits a significant amount of high-energy radi-

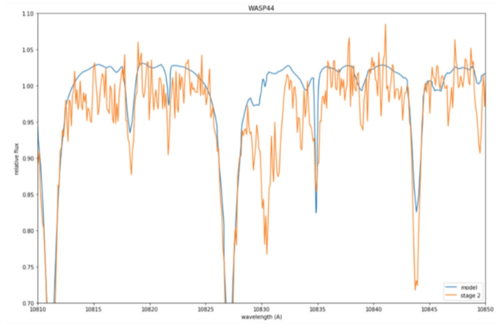

Figure 5. Wavelength-calibrated spectrum.

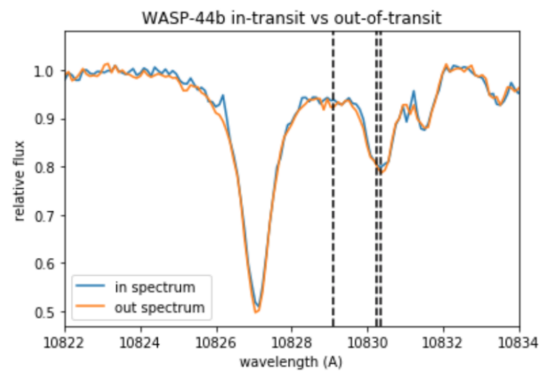

Figure 6. Preliminary result.

ation, which is necessary for populating the metastable state of helium in the planetary atmosphere. Furthermore, we were able to obtain a preliminary result regarding the in transit and out of transit plot after normalization as shown in Figure 6. This preliminary result shows no significant increase in the depth of the 10830 Angstrom line, indicating a non-detection of Helium in WASP-44b's atmosphere. Our typical errors per 0.12-Angstrom wavelength bin were around 1%. Therefore, we can preliminarily rule out excess absorption greater than 1%, which corresponds to a spatial extent of the atmosphere of 1.25 planetary radii. It is possible that the lack of excess Helium absorption is a result of an atmosphere that is slightly enriched by small amounts of heavier species like carbon and oxygen. These are very efficient at cooling down atmospheres, because they have a high amount of atomic transition lines. A cooler atmosphere will mean a lower atmospheric escape rate, and thus a smaller helium signal. Likewise, a low XUV flux rate from the star could also be the cause of a smaller helium abundance. With this preliminary result, our next steps are to correct for telluric contamination of the spectra, and search for any absorption that tracks with the radial velocity of the planet. The useful technique of transmission spectroscopy will continue to be

applied in the Caltech division of geological and planetary sciences.

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