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FIRST RESULTS FROM THE JWST COMPASS (COMPOSITIONS OF MINI-PLANET ATMOSPHERES FOR STATISTICAL STUDY) PROGRAM

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Abstract. The last decade of exoplanet exploration has revealed that planets between the sizes of the Earth and Neptune are the most common in the Galaxy, seemingly bridging the gap between the types of planets in our own Solar System. Therefore, it is of great interest to understand how these planets formed, which we can investigate via their present-day compositions. However, thus far, the atmospheric compositions of these planets have mostly remained a mystery due to observational limitations. Now that we are firmly in the era of JWST, we can begin to measure, in more detail, the atmospheres of these planets to better understand their evolutionary trajectories. Motivated by this opportunity, we designed COMPASS (Compositions of Mini-Planet Atmospheres for Statistical Study), a JWST program to rigorously compare the presence and compositions of atmospheres for these small planets, and the largest Cycle 1 GO program dedicated to the study of exoplanet atmospheres. Our sample consists of 12 super-Earth/sub-Neptune planets, including four pairs of planets in the same system, allowing for robust statistical inferences about this population of planets. I will briefly introduce our sample to showcase the expected diversity in bulk and atmospheric composition. Then, I will present early results from the COMPASS program, highlighting outcomes, challenges, and early lessons learned.

Keywords: exoplanets, atmosphere, transit spectroscopy, JWST, atmospheric composition, sub-Neptunes

1 Introduction

One of the most surprising revelations from the Kepler mission was the ubiquity of super-Earths and sub-Neptunes, two populations of planets with sizes between that of Earth and Neptune ($1 - 3.5\ R_\oplus$) separated by a "radius valley"–a decrease in occurrence of planets with radii between 1.5 and 2.0 $R_\oplus$ (Batalha et al. 2013; Zeng et al. 2017; Fulton & Petigura 2018; Van Eylen et al. 2018). The larger of the two populations, sub-Neptunes ($1.7\ R_\oplus \lesssim R_\mathrm{p} \lesssim 3.5\ R_\oplus$ Fulton & Petigura 2018), are thought to host relatively large, primordial, hydrogen-dominated envelopes (Venturini & Helled 2020), while the smaller super-Earths may possess higher mean molecular weight, "secondary" atmospheres outgassed from their interiors like those of the rocky planets in the Solar System (Rogers et al. 2023). How these two subclasses of planets formed and gave rise to the population we know today is a very active area of research.

Motivated by the prevalence of $1 - 3\ R_\oplus$ planets in general and the new possibilities for understanding their atmospheres unlocked by JWST, we initiated the large JWST Cycle 1 program Compositions of Mini-Planet Atmospheres for Statistical Study (COMPASS; GO-2512, PIs N. E. Batalha & J. Teske), a transmission

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spectroscopy survey of 11 super- Earth/sub-Neptune planets with NIRSpec G395H (our full sample also includes GTO target TOI-175.02 for a total of 12 planets Batalha et al. 2021), which are shown in the mass-radius space in Figure 1. Broadly, the program aims to better understand whether small planets have atmospheres and, if so, the compositional diversity of this population. More specifically, COMPASS aims to (1) map out atmospheric detectability as a function of radius across the small-planet regime, i.e., whether there is a radius below which we stop seeing detectable atmospheric features; (2) explore what the diversity in atmospheric composition implies for the origin(s) of these planets; (3) compare the compositions of "sibling" planets orbiting the same star but that have different radii and periods; and (4) investigate what population-level inferences we can draw from the entire sample. Importantly, the sample was selected with a quantitative, reproducible metric to enable robust inferences about the properties of somewhat cool ($\sim$400 − 1000 K), 1 − 3 $R_\oplus$ planets. More details about the motivation and benefits of our selection method and an example of a simple population-level trend that could be investigated can be found in Batalha et al. (2023).

Here, we present the first observations of the two planets of the TOI-836 system: planet b (Alderson et al. 2024), a hot super-Earth, and planet c (Wallack et al. 2024), a warm mini-Neptune.

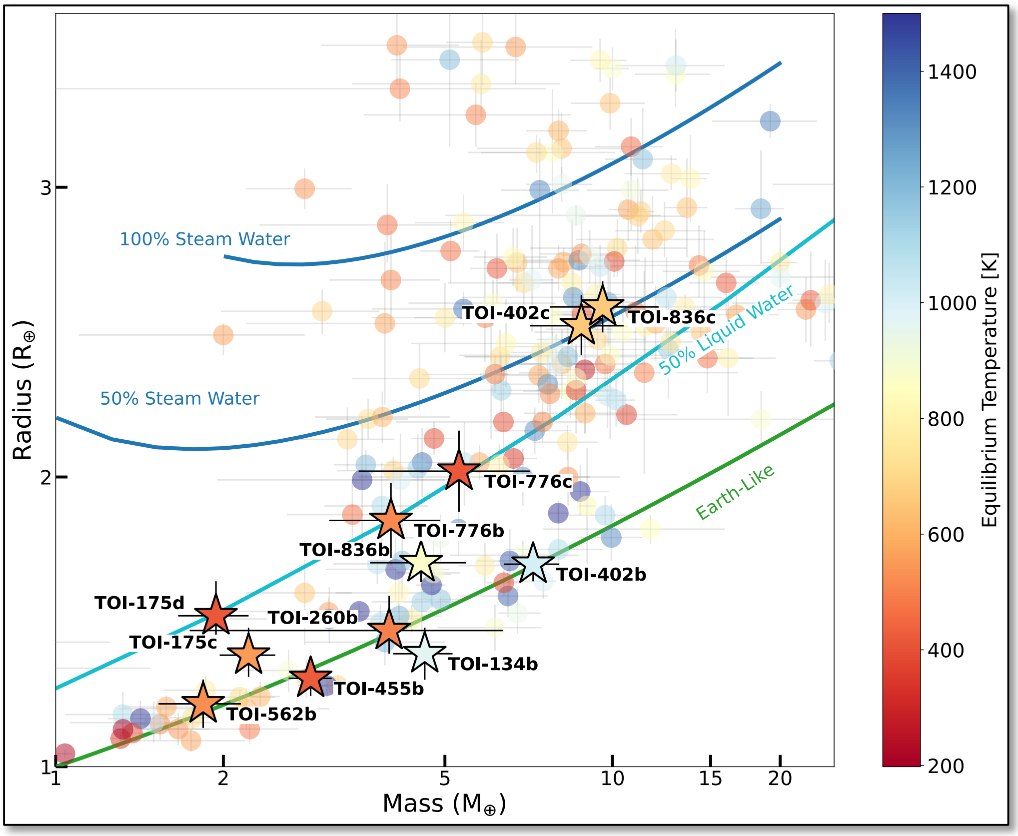

Fig. 1. 11 planets of the COMPASS Program, including GTO target TOI-175.02, in the planet mass-radius space. Exoplanets in the background are all other planets that went through the selection process in Batalha et al. (2021). The color map represents the equilibrium temperature of planets. Theoretical iso-composition lines are shown for Earth-like and 50% liquid water planets (Zeng et al. 2016), and for steam worlds (Aguichine et al. 2021).

2 TOI-836b

We observed two transits of TOI-836b with JWST NIRSpec using the high-resolution (R $\sim$ 2700) G395H mode, which commenced on 2023 March 4 at 18:09 UTC and 2023 March 8 at 13:45 UTC, respectively. These visits were coincidentally separated by one orbital period, considerably less than the 22 day rotation period of TOI-836 (Hawthorn et al. 2023). NIRSpec/G395H provides spectroscopy between 2.87 and 5.14 μm across the NRS1 and NRS2 detectors (with a gap between 3.72 and 3.82 μm). Both observations were taken in NIRSpec Bright

Object Time Series mode using the SUB2048 subarray, F290LP filter, S1600A1 slit, and NRSRAPID readout pattern. Each 5.3 hr observation consisted of 5259 integrations with three groups per integration, and was designed to cover the 1.8 hr transit and sufficient pre- and post-transit baseline.

To check for consistency and ensure robust conclusions, we reduced the data using two independent pipelines: ExoTiC-JEDI (Alderson et al. 2022, 2023) and Eureka! (Bell et al. 2022). Each reduction process is described in detail in Alderson et al. (2024) and follows similar procedures to other NIRSpecG395H transmission spectra analyses. In addition to this, in order to evaluate the power of combining multiple visits, we also produce a joint fit of the Eureka! reduction light curves. We fit both visits simultaneously, but continue to separate NRS1 and NRS2 to account for any offsets between the two detectors and the differing systematic effects.

We fit our observations with a grid of transmission spectra using the open-source PICASO package (Batalha et al. 2019). Figure 2 shows the results of this fit. With the combined spectra, we are further able to rule out metallicities < 250 time solar and < 380 times solar, for ExoTiC-JEDI and Eureka!, respectively, corresponding to mean molecular weights of $\sim 6-9$ g/mol.

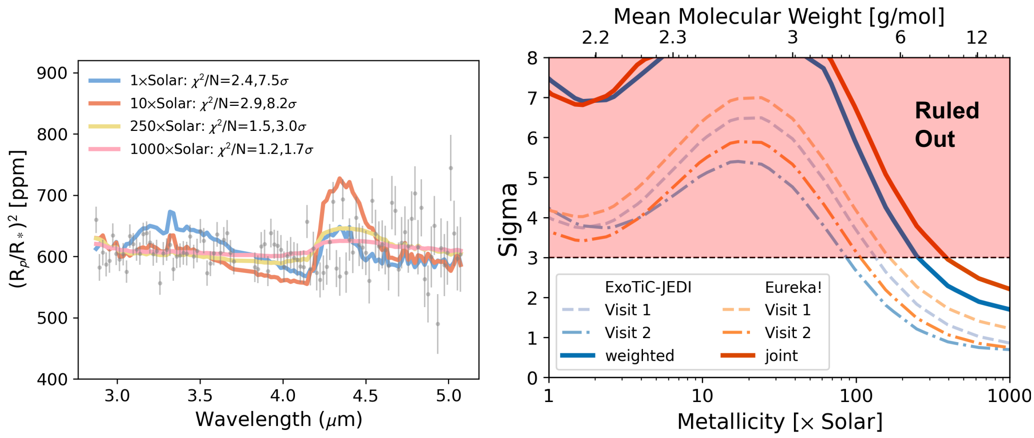

Fig. 2. Left panel: For four of the metallicity cases, we show the spectra relative to the weighted data from ExoTiC-JEDI. We also indicate the χ^2/N and σ for reference. For a single choice of opaque pressure level (0.1 bar), we show the parameter space that can be ruled out in metallicity. The blue lines show the reductions for ExoTiC-JEDI (Visits 1, 2, and weighted) and the orange lines show the reductions for Eureka! (Visits 1, 2, and joint). The black dashed line indicates the 3σ level, below which we are unable to confidently rule out models. Ultimately, our data rule out metallicities < 250 times solar for TOI-836b, corresponding to a mean molecular weight of ~ 6 g/mol. Adapted from Alderson et al. (2024).

3 TOI-836c

One transit of TOI-836c was obtained by the Near-Infrared Spectrograph (NIRSpec) G395HF290LP grating on 2023 February 16 in the NIRSpec Bright Object Time series mode with the SUB2048 subarray and the NRSRAPID readout pattern. We utilized three groups per integration, with 6755 integrations, and a total exposure time of 6.8 hours. The spectral traces using NIRSpec G395H (2.87-5.18 μm) are taken across two separate detectors, NRS1 and NRS2, with a small gap in wavelength coverage (between 3.72 and 3.82 μm) caused by the gap between the two detectors.

We reduced our observations using three independent pipelines to determine the robustness of our derived best-fit parameters and transmission spectrum: Eureka! (Bell et al. 2022), our ExoTiC-JEDI (Alderson et al. 2022, 2023) reduction, and Aesop (M. K. Alam et al. 2024, in preparation). Detailed results for each individual reduction are given in Wallack et al. (2024).

We fit our observations with a grid of transmission spectra using the open-source code PICASO 3.1 (Batalha et al. 2019; Mukherjee et al. 2023). For planet c, we also investigate the effect a high-altitude cloud deck, motivated by the potential presence of photochemically produced hazes. The results of our fit are shown in Figure 3. With this method, we are able to rule out metallicities < 175 time solar, unless high altitude clouds aerosols are present, in which case the metallicity is unconstrained.

Results of this analysis are shown in Figure 3.

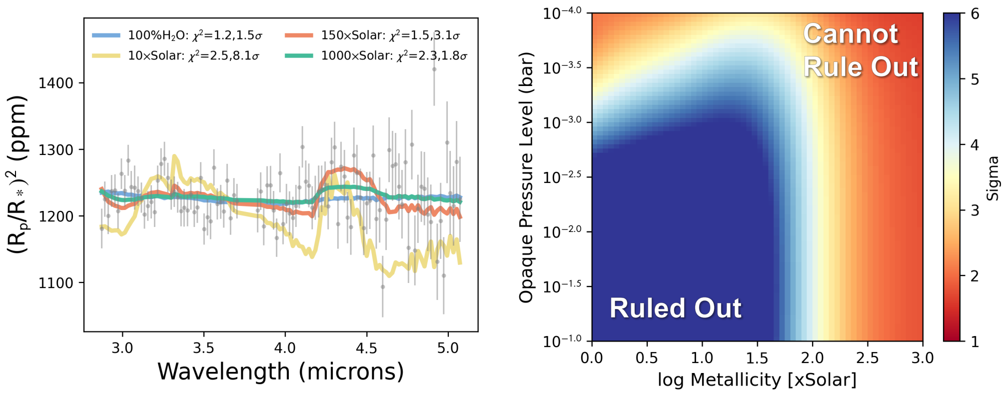

Fig. 3. Left panel: we show the transmission spectrum for the nominal Eureka! case along with four example models depicting 10×, 150×, and 1000× solar metallicity, as well as a 100% H_2O model. In the legend, we also show the χ^2/N and the corresponding σ at which the model can be confidently ruled out. In the right panel we show the full parameter space of opaque pressure level and metallicity. Here the color scale of the heatmap similarly indicates at what σ each model can be confidently ruled out. Ultimately, we are unable to rule out metallicities $> 175\times$ solar for TOI-836c ($\log[M/H] > 2.2$). Adapted from Wallack et al. (2024).

4 Conclusions

In this talk, we presented the first results of the JWST COMPASS Program, focusing on two planets from the same system: TOI-836b (Alderson et al. 2024) and TOI-836c (Wallack et al. 2024). We do not detect features in either of the TOI-836 spectra, but we can still place constraints on their atmospheres: $> 250\times$ solar for TOI-836b, and $> 175\times$ solar for TOI-836c. We are working at the limits of what JWST can detect and are seeing excess noise in the data that we are working to understand.

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