Lava Lamps: Early Observations of TOI431b & TOI1416b in Secondary Eclipse for Possible Silicate Atmospheres

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Summary:

We are observing 10 rocky exoplanets with JWST MIRI/LRS with irradiation temperatures above 1,500 K in secondary eclipse to search for silicate vapor atmospheres and to further our understanding of ultra-hot terrestrial planet atmosphere formation and retention. Observations for TOI431b have found an eclipse depth that is shallower than expected, suggesting that it may possess a tentative atmosphere.

Background

- Observing dayside emission for rocky exoplanets is effective at detecting atmospheres [1-2].
- Atmospheres on rocky exoplanets impose an albedo and potentially recirculate heat, cooling their daysides.
- At irradiation temperatures above 1700K, planets may have silicate atmospheres made of evaporated rock from their surfaces [3-5].
- These silicate atmospheres are not currently well constrained (greenhouse effect, clouds, heat redistribution), and observations are needed to provide more clarity.

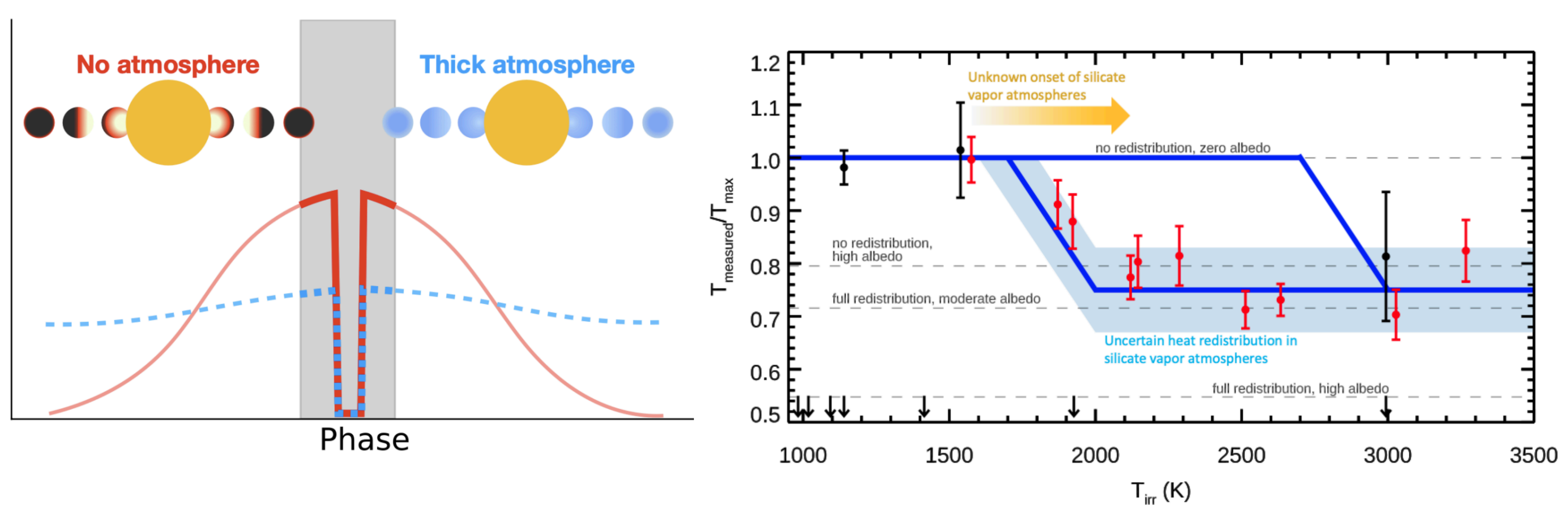


Fig 1: Left: Two cases for secondary eclipse observations. A terrestrial planet with no atmosphere (red solid line) is expected to have a hot dayside, cold nightside, and little to no heat redistribution. Adding an atmosphere (blue dotted line) increases the amount of heat redistribution, which cools the dayside and warms the nightside. Observing just the secondary eclipse to determine if the planet has a hot or cold dayside temperature is enough to distinguish between these two scenarios. Right: Dayside temperature relative to the maximum possible temperature (zero albedo, instant re-radiation) is plotted as a function of irradiation temperature. The targets of this program are the red circles shown as simulated points with expected uncertainties (error bars scaled from real JWST data taken in Cycle 1). The black circles are existing measurements from Spitzer (in increasing order of temperature: LHS 3844b, GJ 1252b, and K2-141b). Black arrows at the bottom of the plot represent the irradiation temperatures of planets that are being targeted for MIRI thermal emission measurement in Cycles 1 and 2.

Methods

- The data reduction and eclipse fitting were both done with the "Eureka!" exoplanet time-series observation pipeline [6].
- Once the eclipse itself was fit and the depth was extracted, we could begin a fit for the dayside temperature of the planet using the equation below:

$$\frac{F_p}{F_s} = \left(\frac{R_p}{R_s}\right)^2 \cdot \frac{\int \frac{\pi \cdot B_p(T_p, \lambda)}{hc/\lambda} \cdot W_\lambda \, d\lambda}{\int \frac{M_s(T_s, \log g, [M/H], \lambda)}{hc/\lambda} \cdot W_\lambda \, d\lambda}$$

Where W_λ is the throughput of MIRI/LRS, $B_p(T_p, \lambda)$ is the planetary blackbody intensity, and M_s is the stellar spectrum [7]. The stellar spectra were interpolated from the PHOENIX grid [8] using the Python package pysynphot.

- This temperature can then be expanded and compared to the maximum dayside temperature to calculate a temperature scaling factor **R** such that:

$$T_{p,\mathrm{dayside}} = T_{\max} \cdot \mathcal{R} = \left(\frac{2}{3}\right)^{\frac{1}{4}} \cdot \frac{T_s}{\sqrt{a/R_s}} \cdot \mathcal{R}$$

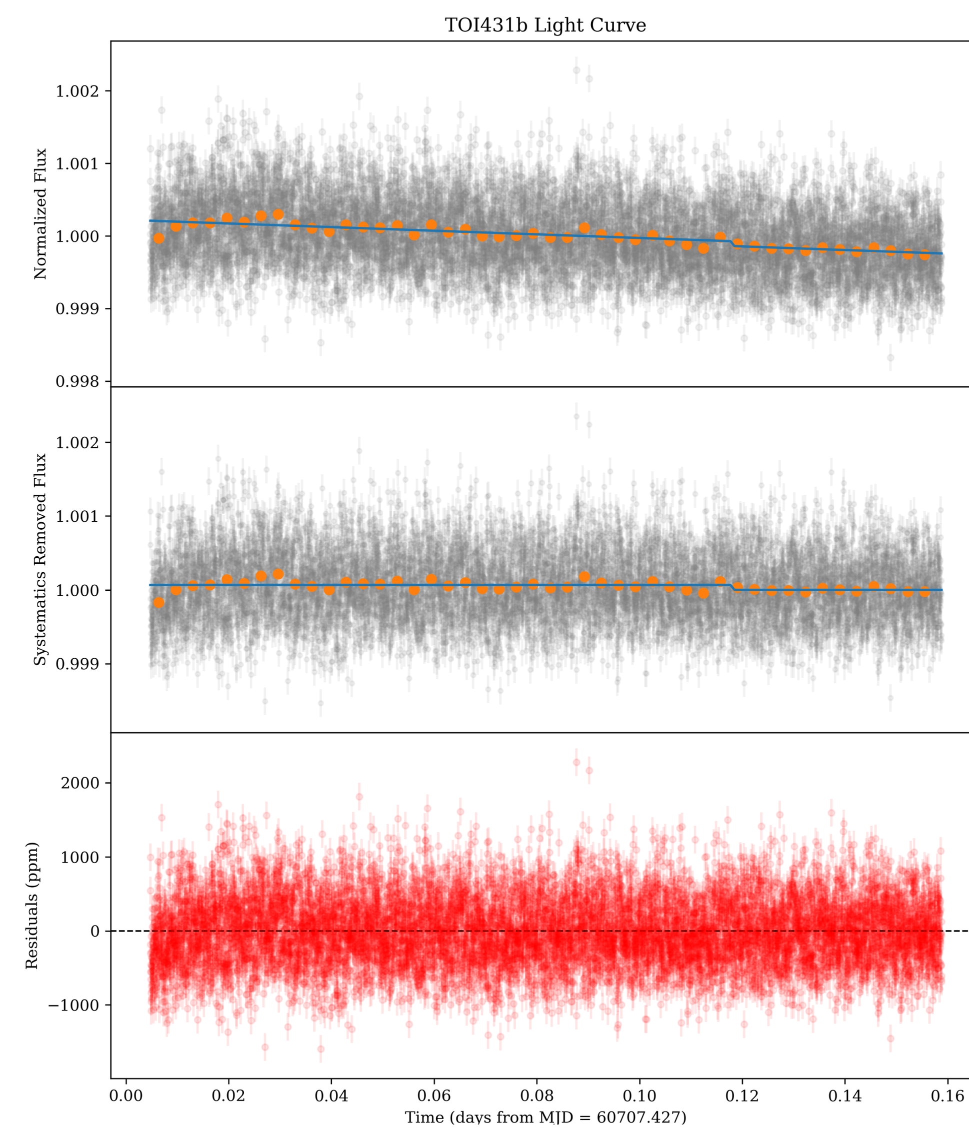
$$\mathcal{R} = \left(\frac{2}{3}\right)^{-\frac{1}{4}} \cdot (1 - A_B)^{\frac{1}{4}} \cdot \left(\frac{2}{3} - \frac{5}{12}\varepsilon\right)^{\frac{1}{4}}$$

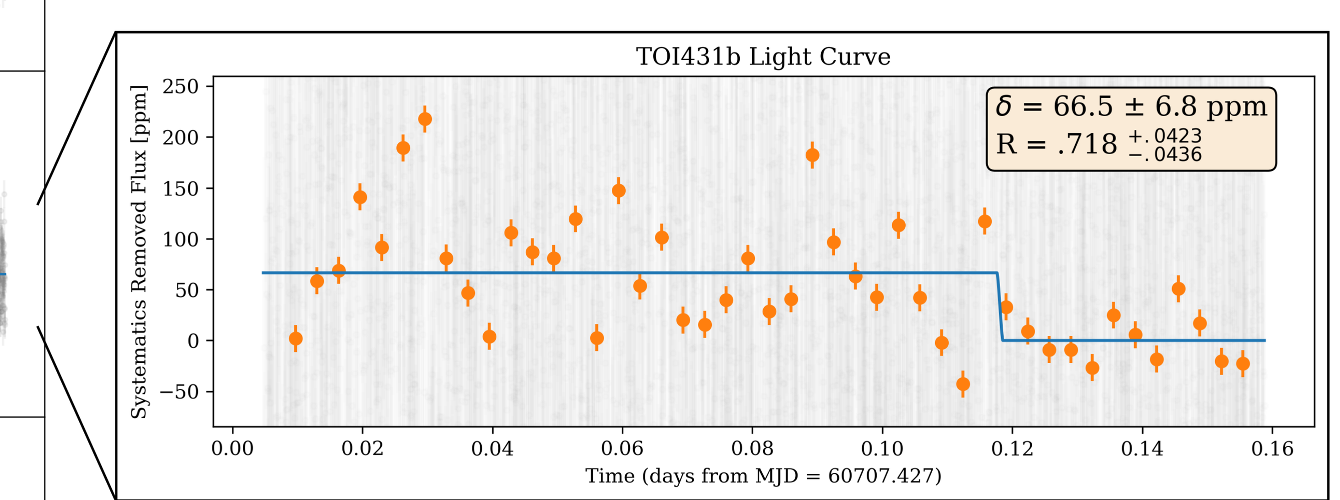
Where a is the planet's semi-major axis, R_s is the star's radius, A_B is the planet's bond albedo, and ε is the heat recirculation efficiency [9].

- These equations are normalized such that when the planet's bond albedo and heat recirculation efficiency are both 0, R = 1, or that the dayside temperature is in agreement with the maximum expected possible temperature.
- **A planet with an R value significantly less than 1 is indication of a potential planet atmosphere**.

Results

For TOI431b, we found that the planet had an eclipse depth of 66.5 ± 6.8 ppm which corresponds to a dayside temperature of 1748^{+103}_{-106} K. Combining these, an R value of ~.718. All of this points towards there being **some type of cooling mechanism present that is lowering the dayside temperature of the planet below its maximum value.** Additionally, this shallow eclipse has also been found in Spitzer observations [10]. The eclipse light curve and bond albedo vs. heat redistribution efficiency are shown below in Figure 2.





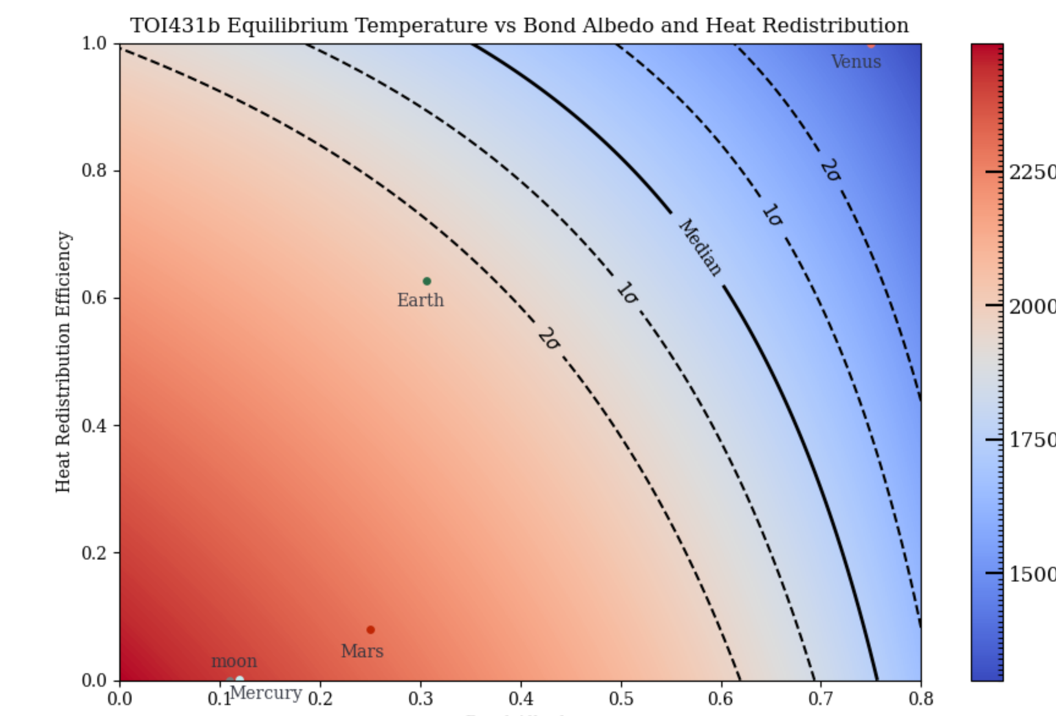
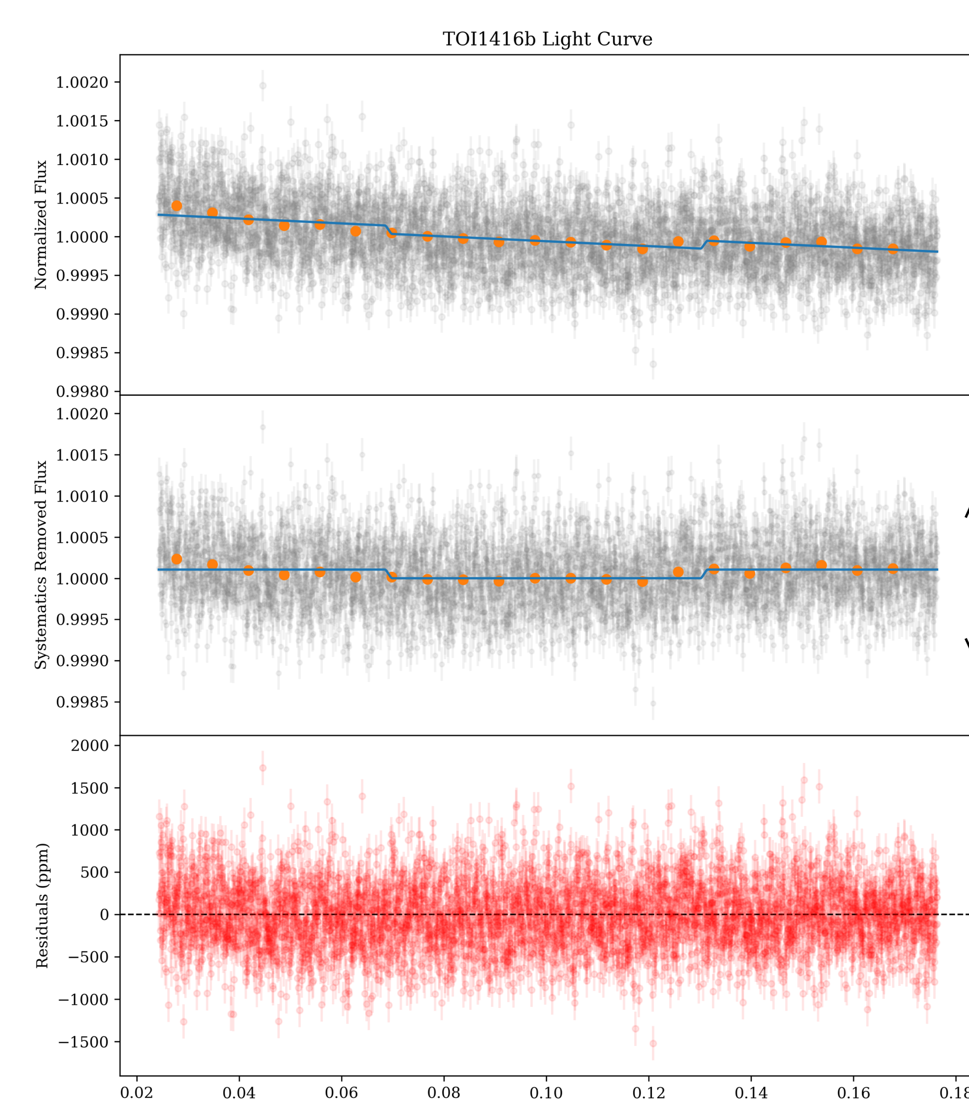
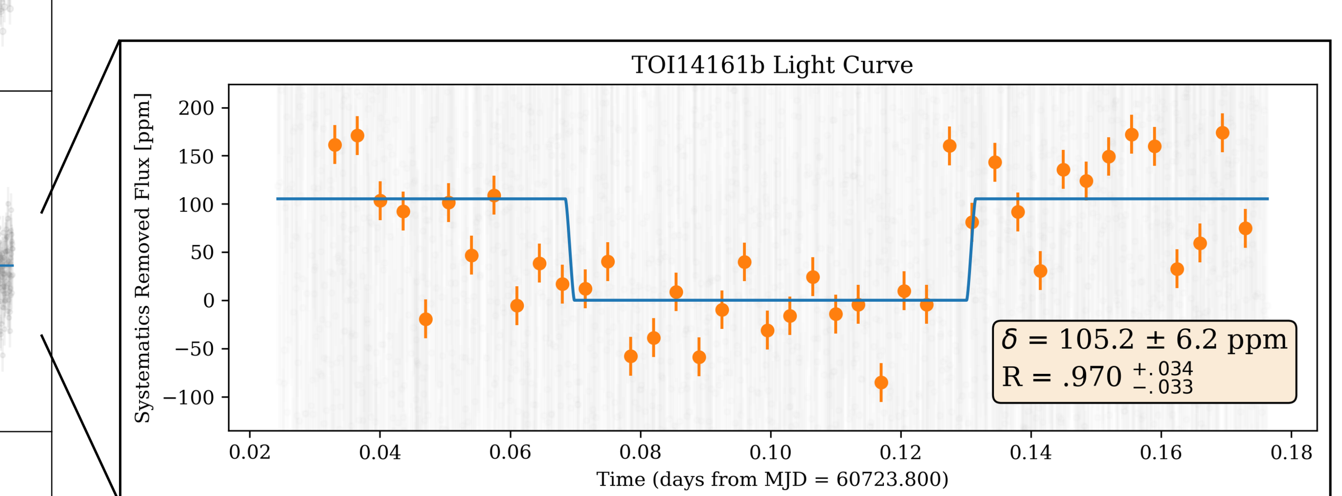


Fig 2: Left: Dayside emission observation for TOI431b. A linear slope fit was done on the data, and the eclipse occurs near the end of the observation window and is only partial. Right: Contour plot showing over plotting the determined dayside temperature with the respective relationship between the planet's bond albedo and heat redistribution efficiency. This demonstrates that the planet has some type of cooling mechanism that is lowering the temperature of the planet below that of its maximum value and potentially indicative of a vapor atmosphere.

For TOI1416b, it was derived that the planet had an eclipse depth of 105 ± 6.2 ppm which corresponds to a dayside temperature of $1894^{+67.9}_{-66.2}$. Combining these, an R value of ~.97. This suggests the planet consists of just a bare rock without a vapor atmosphere to cool the dayside. The eclipse light curve and bond albedo vs. heat redistribution efficiency are shown below in Figure 3.





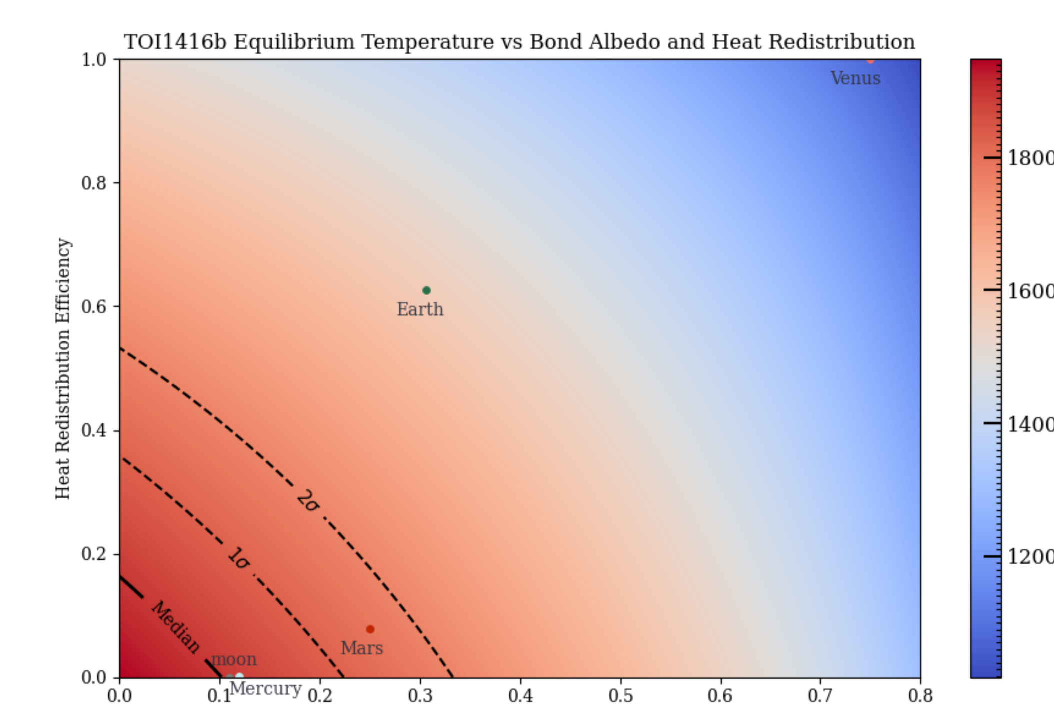


Fig 3: Left: Dayside emission observation for TOI1416b. A linear slope fit was done on the data, and the eclipse is centered within the observation window. Right: Contour plot showing over plotting the determined dayside temperature with the respective relationship between the planet's bond albedo and heat redistribution efficiency. This demonstrates that the planet is close to its maximum possible temperature and likely does not posses a vapor atmosphere.

Next Steps

- These planets are only a small piece of the full project, and a conglomeration of all 10 planets with this level of analysis is still ongoing. Planets that posses lower eclipse depths than expected (like TOI431b) may be followed up with additional observations to improve the SNR. Combining observations across differing instruments (Hubble, Spitzer, etc.) will allow for the best constrained orbital parameters and eclipse depths for all planets within this project.
- These observations are also being done simultaneously on SPARTA [11] in order to do the reduction using multiple pipelines for consistency. Stay tuned for more LAVA LAMPS!

[1] Koll et al. (2019), The Astrophysical Journal, 886, 140. [2] Mansfield et al. (2019), The Astrophysical Journal, 886, 141. [3] Schaefer & Fegley,(2009), The Astrophysical Journal Letters, 703, L113. [4] Miguel et al. (2011) The Astrophysical Journal Letters, 742, L19. [5] Ito et al. (2015) The Astrophysical Journal, 901, 144. [6]Bell et al. (2022), Journal of Open Source Software, 7(79), 4503. [7] Xue et al. (2024), The Astrophysical Journal Letters, 973, L8 [8] Allard et al. (2012), ESPTA, 370, 2765. [9] Cowan & Agol. (2011), The Astrophysical Journal, 729, 54. [10] Monaghan et al. (2025), The Astrophysical Journal, 169, 239. [11] E. M.-R. Kempton et al. (2023), Nature, 620, 67.