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Hazy Skies, Hidden Signs: Assessing Haze-Driven Habitability and the Concealment of Biosignatures on TOI-700 d

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Abstract. The atmospheric characterization of rocky exoplanets like TOI-700 d faces two major challenges: (1) stellar surface heterogeneities – such as spots or faculae – can mimic or obscure spectral features of the planetary atmosphere, and (2) ultraviolet variability drives photochemical processes that are critical for habitability and prebiotic chemistry. In this presentation, we examine both aspects in the specific context of TOI-700 d. On the photochemistry front, we use 1D photochemical-climate simulations to show that haze formation in TOI-700 d's atmosphere is highly sensitive to surface pressure (0.5–4.0 bar), CH_4/CO_2 ratios, and stellar UV activity. Moderate CH_4/CO_2 values (~0.1–0.3) favor the production of UV-shielding hazes, but flares rapidly dissociate methane, reducing haze opacity by more than 90% compared to quiescent conditions and increasing near-UV surface flux. Our results highlight that atmospheric pressure is not a standalone parameter but interacts dynamically with stellar UV activity and composition to establish an "optimal window" for simultaneous habitability and prebiotic chemistry: at 2–4 bar under moderate flares, remnant haze (though significantly depleted by flares) and methane sustain temperatures > 285 K, enabling extremophile survival (e.g., D. radiodurans) while permitting sufficient surface UV flux for RNA precursor synthesis. In parallel, we simulate the effects of unocculted starspots and faculae on transmission spectra and find that stellar contamination can alter observed signals by up to 50 ppm in optical. These effects can mimic the broadband slopes produced by hazes or obscure weak molecular features (e.g., CH_4, CO_2), introducing spectral degeneracies. Features attributed to atmospheric aerosols may instead arise from stellar heterogeneities, while genuine molecular signatures may remain hidden. Together, our results underscore that retrieving atmospheric properties for TOI-700 d requires accounting for both internal photochemical feedback and external stellar variability. Disentangling these effects is essential to avoid false positives in the search for biosignatures.

Resumo. A caracterização atmosférica de exoplanetas rochosos como TOI-700 d enfrenta dois grandes desafios: (1) heterogeneidades na superfície estelar – como manchas ou fáculas – podem imitar ou ocultar assinaturas espectrais da atmosfera planetária e (2) a variabilidade ultravioleta impulsiona processos fotoquímicos que são críticos para a habitabilidade e para a química pré-biótica. Nesta apresentação, examinamos ambos os aspectos no contexto específico de TOI-700 d. No campo da fotoquímica, utilizamos simulações 1D acopladas de clima e fotoquímica para mostrar que a formação de neblina na atmosfera de TOI-700 d é altamente sensível à pressão superficial (0,5–4,0 bar), às razões CH_4/CO_2 e à atividade UV da estrela. Valores moderados de CH_4/CO_2 (~0,1–0,3) favorecem a produção de neblinas que bloqueiam UV, mas flares dissociam rapidamente o metano, reduzindo a opacidade da neblina em mais de 90% em comparação com condições quiescentes e aumentando o fluxo de UV próximo que chega à superfície. Nossos resultados destacam que a pressão atmosférica não é um parâmetro isolado, mas interage dinamicamente com a atividade UV estelar e a composição para estabelecer uma "janela ótima" para habitabilidade e química pré-biótica simultâneas: entre 2–4 bar sob flares moderados, a neblina remanescente (embora bastante reduzida pelos flares) e o metano sustentam temperaturas > 285 K, permitindo a sobrevivência de extremófilos (por exemplo, *D. radiodurans*) ao mesmo tempo em que possibilitam fluxo suficiente de UV na superfície para a síntese de precursores de RNA. Em paralelo, simulamos os efeitos de manchas e fáculas não ocultadas nos espectros de transmissão e constatamos que a contaminação estelar pode alterar os sinais observados em até 50 ppm no óptico. Esses efeitos podem imitar as inclinações de espectro produzidas por neblinas ou obscurecer assinaturas moleculares fracas (por exemplo, CH_4, CO_2), introduzindo degenerescências espectrais. Assinaturas espectrais atribuídas a aerossóis atmosféricos podem, na verdade, surgir de heterogeneidades estelares, enquanto assinaturas moleculares reais podem permanecer escondidas. Em conjunto, nossos resultados reforçam que recuperar propriedades atmosféricas de TOI-700 d exige considerar tanto o feedback fotoquímico interno quanto a variabilidade estelar externa. Separar esses efeitos é essencial para evitar falsos positivos na busca por bioassinaturas.

Keywords. Planets and satellites: atmospheres – Planets and satellites: composition – Astrobiology – Ultraviolet: planetary system – Planets and satellites: individual: TOI-700 d

1. Introduction

M dwarfs are numerous in the Galaxy and their long main-sequence lifetimes make them promising hosts for habitable planets. Their small radii and close-in habitable zones increase the depth and frequency of planetary transits, which favors atmospheric characterization by transmission spectroscopy. On the other hand, these cool stars can emit strong high-energy radiation, especially in UV and XUV, that may erode atmospheres and modify their chemistry over time.

The TOI-700 system is an M2.5 V star with four known planets, two of which are in the classical habitable zone. TOI-700 d has a radius close to Earth's, receives about 86% of the solar flux at Earth, and orbits a star that appears relatively quiet in X-rays compared to the modern Sun. This combination makes TOI-700 d an interesting laboratory for testing how stellar UV flux and atmospheric pressure influence surface habitability and the detectability of biosignatures.

In the present work, we investigate two atmospheric scenarios for TOI-700 d: an Archean-like, methane-rich atmosphere and a modern Earth-like atmosphere (we refer the reader to our publicly available paper, Sumida et al. 2025, for a complete and in-depth discussion.). For each scenario, we explore a range of surface pressures and two UV regimes that represent a quiescent star and a flare-enhanced state. Our goal is to link three aspects: (i) climate and surface temperature, (ii) the UV environment at the surface and its biological impact, and (iii) the strength of spectral features in transmission spectra.

2. Methods

2.1. Photochemistry–climate simulations

We use the 1D Photochemical Model coupled to the `Atmos` climate model (Arney et al. 2016) to compute self-consistent atmospheric profiles. The photochemical module includes hundreds of reactions and tens of chemical species, with different networks for the Archean and modern Earth-like compositions. The code iterates between chemistry and climate until both temperature and abundances converge.

The stellar and planetary parameters for TOI-700 d are taken from Gilbert et al. (2020). For the stellar spectrum we adopt the M3 V template used by Arney et al. (2016), which is a good proxy for the M2.5 V host star. The model assumes globally averaged conditions, with solar zenith angles chosen to reproduce the present-day terrestrial ozone column in the modern case.

We explore four surface pressures (P_s = 0.5, 1.0, 2.0, and 4.0 bar) and two atmospheric compositions:

- Archean-like atmospheres with CH_4/CO_2 ratios above 0.1, which favor the formation of organic hazes;
- Modern Earth-like atmospheres with present-day levels of O_2 and CO_2.

For each composition and pressure we compute two UV scenarios using the `Atmos` amplification factor f_{UV}:

1. $f_{UV} = 1$ – a quiescent star with UV flux similar to the template spectrum;
2. $f_{UV} = 10$ – a flare-enhanced state where near-UV radiation is increased by one order of magnitude, consistent with GALEX-based estimates of flare-to-quiescent ratios for M2–M3 dwarfs (Rekhi et al. 2023).

2.2. Planetary UV and biological effective dose

To quantify the biological impact of surface UV radiation, we compute the biologically effective irradiance, E_{eff}, by weighting the surface flux with action spectra for *Escherichia coli* and *Deinococcus radiodurans*. For each atmosphere, we integrate E_{eff} over one generation time (20 min for *E. coli*, 100 min for *D. radiodurans*) and compare the resulting dose with laboratory thresholds corresponding to 10% survival (Gascon et al. 1995). This allows us to identify regions in the parameter space where at least part of the microbial population could persist at the surface.

2.3. Synthetic transmission spectra

We use the gas mixing ratios and haze properties from the `Atmos` simulations as input to the Planetary Spectrum Generator (PSG) in its GlobES mode (Villanueva et al. 2018). PSG computes transmission spectra for TOI-700 d, including major molecules such as H_2O, CH_4, CO_2, O_3, O_2, and others. The resulting spectra are used to evaluate how hazes and ozone change the strength of biosignature bands and the overall transit depth.

3. Results

3.1. Temperature–pressure profiles and surface liquid water

Fig. 1 shows the T–P profiles for TOI-700 d for the four surface pressures considered. Each panel compares Archean-like and modern Earth-like atmospheres under both quiescent and flare-enhanced UV regimes.

Across all scenarios, surface temperatures remain above the freezing point of water, and in many cases, they reach or exceed 285 K. This means that, for a wide range of pressures and compositions, TOI-700 d can maintain liquid water at the surface. This is consistent with the fact that the planet lies inside the habitable zone of its host star: the stellar flux is high enough to prevent global freezing, while the atmosphere provides additional greenhouse warming.

3.2. Atmospheric structure and photochemistry

All modeled atmospheres reach surface temperatures compatible with liquid water. Differences between the cases are mainly related to the dominant opacity sources and the vertical distribution of key molecules.

In the Archean-like simulations with $f_{UV} = 1$, methane is abundant and the CH_4/CO_2 ratios are high enough to trigger intense formation of organic hazes. These hazes concentrate at high altitudes and strongly absorb in the UV and blue part of the spectrum. As a result, they provide efficient shielding for the lower atmosphere and the surface. In addition, they modify the vertical profiles of methane and related species through photochemistry.

When the UV flux is increased to $f_{UV} = 10$, photolysis partially destroys methane and reduces haze production. The atmosphere still remains warm enough for liquid water, but the UV optical depth of the haze layer decreases. For the modern Earth-like composition, the situation is reversed: under low UV, ozone columns are modest and UV shielding is limited, while in the high-UV regime the production of O_3 becomes more efficient and a stronger ozone layer is formed.

3.3. Surface UV and the window for survival and prebiotic chemistry

In Fig. 2, we show E_{eff} as a function of surface pressure for the two bacteria. In hazy Archean atmospheres with $f_{UV} = 1$, the biologically effective doses are many orders of magnitude lower than the experimental lethal doses for both organisms. This means that thick hazes can keep the surface UV field at very safe levels, even for the most sensitive microbe, across all pressures considered.

In the modern Earth-like atmospheres, the quiescent case produces higher E_{eff} because ozone is less abundant. Increasing the UV flux to $f_{UV} = 10$ enhances ozone production and the resulting layer is able to attenuate the surface UV dose, especially at higher pressures. In this regime both bacteria can survive for most pressures, although the margin is smaller than in the hazy Archean scenarios.

The most hostile conditions arise in the Archean atmosphere with $f_{UV} = 10$. Here, haze is weakened by photolysis, but ozone is still not as effective as in the modern case. For this combination we find that *E. coli* would not survive at the surface for any of the pressures explored, while *D. radiodurans*, which is much more resistant to UV, can tolerate only the denser atmospheres at 2 and 4 bar.

Beyond the question of habitability, we also examine whether the surface-level near-UV flux is high enough to trigger prebiotic

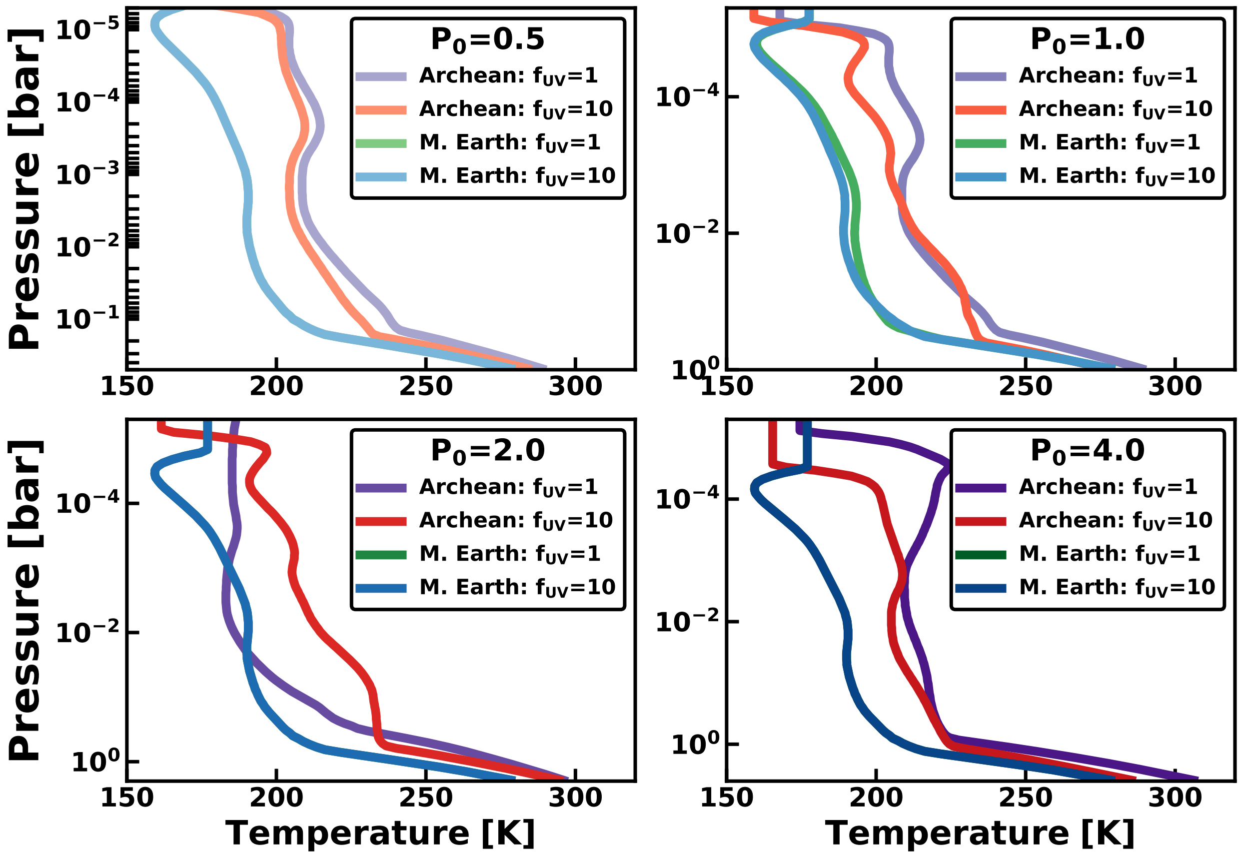

Figure 1. Temperature–pressure profiles for TOI-700 d at four surface pressures (P_0 = 0.5, 1.0, 2.0, and 4.0 bar). Each panel shows Archean-like and modern Earth-like atmospheres under quiescent (f_{UV} = 1) and flare-enhanced (f_{UV} = 10) UV regimes.

photochemistry. According to Rimmer et al. (2018), a minimum of 4.5×10^{-2} W m^{-2} in the 200–280 nm range is needed to drive the photochemical pathways that generate RNA precursors. As shown in Figure 3, this requirement is met only in the Archean-like scenario with f_{UV}=10, and only at elevated surface pressures (2–4 bar), where *D. radiodurans* remains viable.

3.4. Transmission spectra and biosignature detection

The synthetic transmission spectra (Figs. 4 and 5) illustrate how hazes and ozone control the observable features of TOI-700 d. In Archean-like models with strong haze, the continuum level increases and the Rayleigh slope in the blue is partially masked by aerosol absorption. Molecular bands of CH_4 and CO_2 become shallower, especially at short wavelengths where the haze is optically thick. This makes the detection of individual gas features more difficult, even though the atmosphere as a whole produces a deeper transit.

In modern Earth-like atmospheres, haze is much weaker and the spectra show clearer molecular signatures. Under high UV (f_{UV} = 10), the stronger ozone layer imprints both the broad Hartley band in the UV and mid-infrared absorption near 9.6 μm. These features would be potential diagnostics of an oxidizing, O_2-rich atmosphere, but their amplitudes are still small in terms of transit depth.

Using the PSG simulations, we estimate that, for TOI-700 d, most of these spectral features are at the level of a few tens of ppm in transit depth. Given the small size of the star and the planet, detecting them with current facilities like JWST would require an impractically large number of transits. Nevertheless, the trends found here are relevant for other, more favorable systems around M dwarfs and for future telescopes with higher collecting areas.

4. Conclusions

We have used coupled photochemistry–climate simulations and synthetic spectra to study possible atmospheres for TOI-700 d under different UV environments and surface pressures. The main conclusions can be summarized as follows:

- All modeled scenarios maintain surface temperatures compatible with liquid water, for both Archean-like and modern Earth-like compositions.
- In low-UV Archean atmospheres, thick organic hazes provide strong UV shielding and drastically reduce the biologically effective dose at the surface. In this regime, both *E. coli* and *D. radiodurans* would survive across the range of pressures explored.
- In modern atmospheres, enhanced UV leads to more efficient ozone formation, which also protects the surface. The most harmful case is the Archean atmosphere under high UV, where weakened hazes and low ozone result in sterilizing conditions for *E. coli*.
- Beyond present-day habitability, only the Archean-like case with f_{UV}=10 produces sufficient near-UV flux (in the 200–280 nm range) to initiate prebiotic photochemistry. This occurs at higher surface pressures (2–4 bar), where *D. radiodurans* still persists, suggesting that both abiogenesis and early microbial resilience could be supported simultaneously depending on the atmospheric composition and pressure.

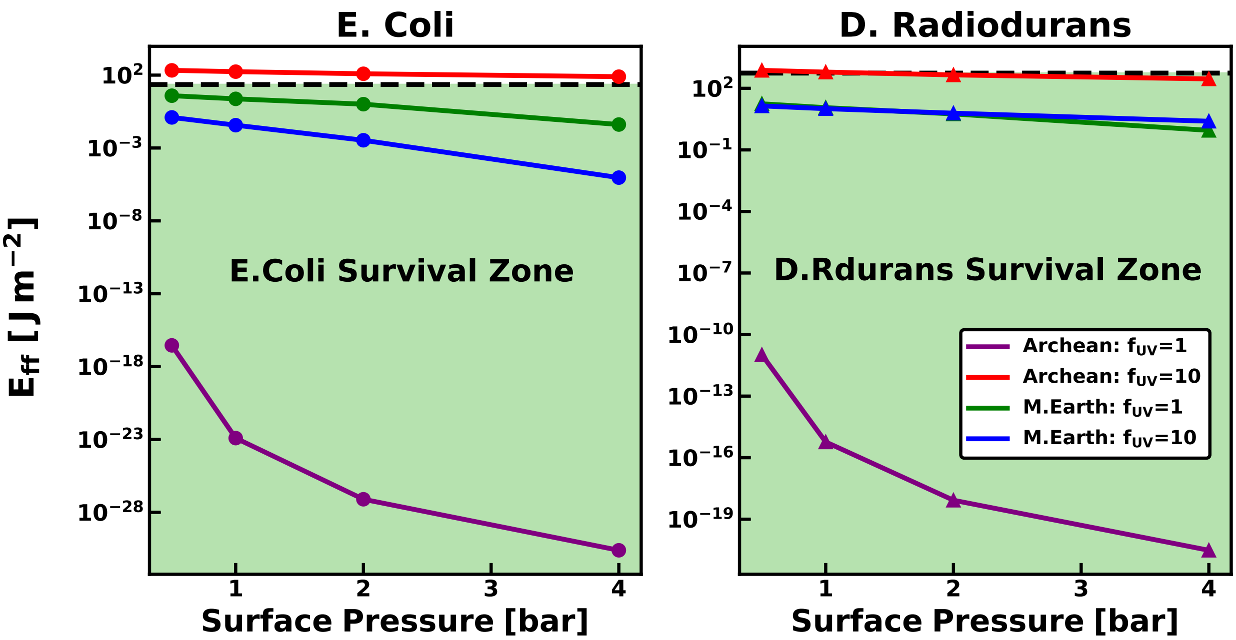

Figure 2. Biologically effective irradiance as a function of surface pressure for the different atmospheric models of TOI-700 d, for *E. coli* (left) and *D. radiodurans* (right). The shaded green region indicates doses compatible with at least 10% survival.

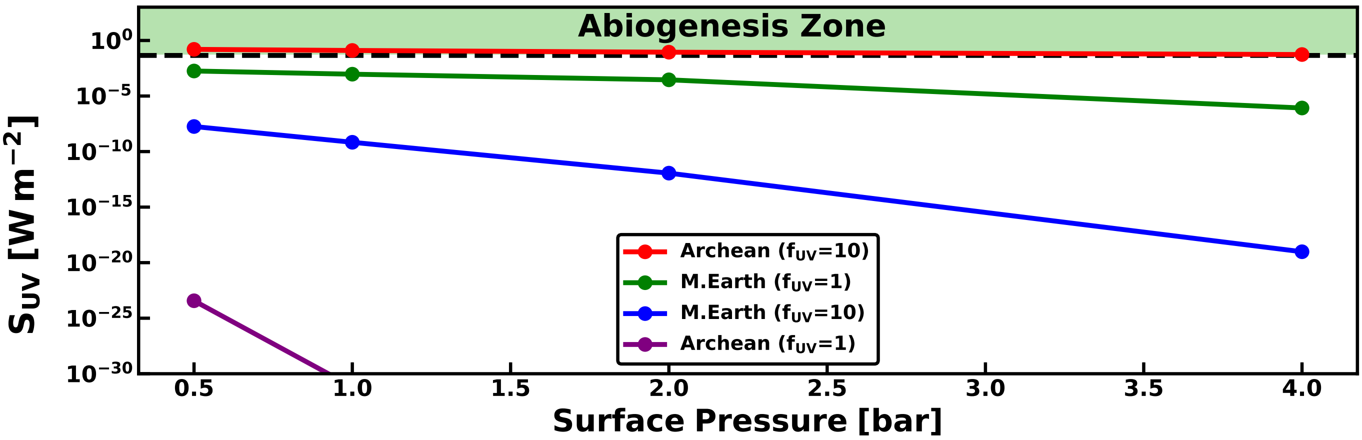

Figure 3. The integrated UV flux reaching TOI-700 d's surface, spanning wavelengths from 200 to 280 nm, as a function of surface pressure for the different atmospheric models. The black dashed line indicates the minimum UV flux required for the formation of RNA precursors.

- Hazes and ozone have opposite effects on the transmission spectra. Hazes hide molecular bands but increase the overall transit depth, whereas ozone produces sharper features but requires favorable conditions to build up.

Overall, the study shows that UV flux and atmospheric pressure cannot be treated independently when assessing habitability, prebiotic potential, and biosignature detectability on M-dwarf planets. For TOI-700 d, a wide range of atmospheres could support liquid water and, in many cases, allow microbial survival at the surface. At the same time, only specific high-UV, high-pressure Archean-like conditions provide sufficient near-UV flux for prebiotic photochemistry, while photochemically produced hazes may make the detection of key biosignature gases more challenging, even if the underlying atmosphere is biologically active.

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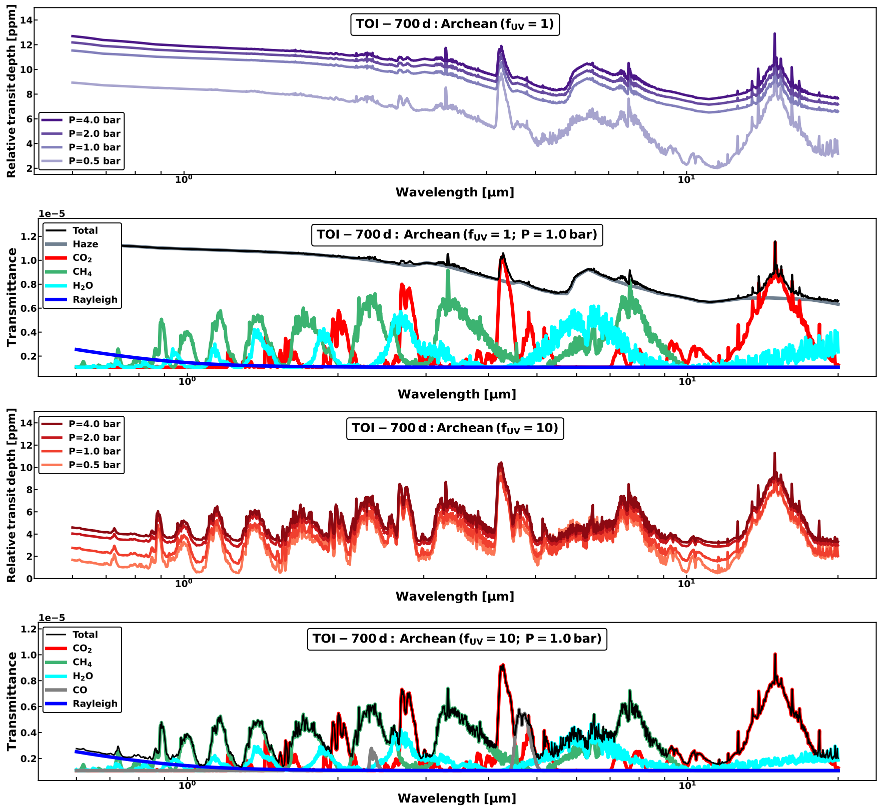

Figure 4. Transmission spectra for Archean-like atmospheres of TOI-700 d at 1 bar, comparing low-UV (f_{UV} = 1) and high-UV (f_{UV} = 10) cases. Organic hazes increase the continuum level and obscure molecular bands.

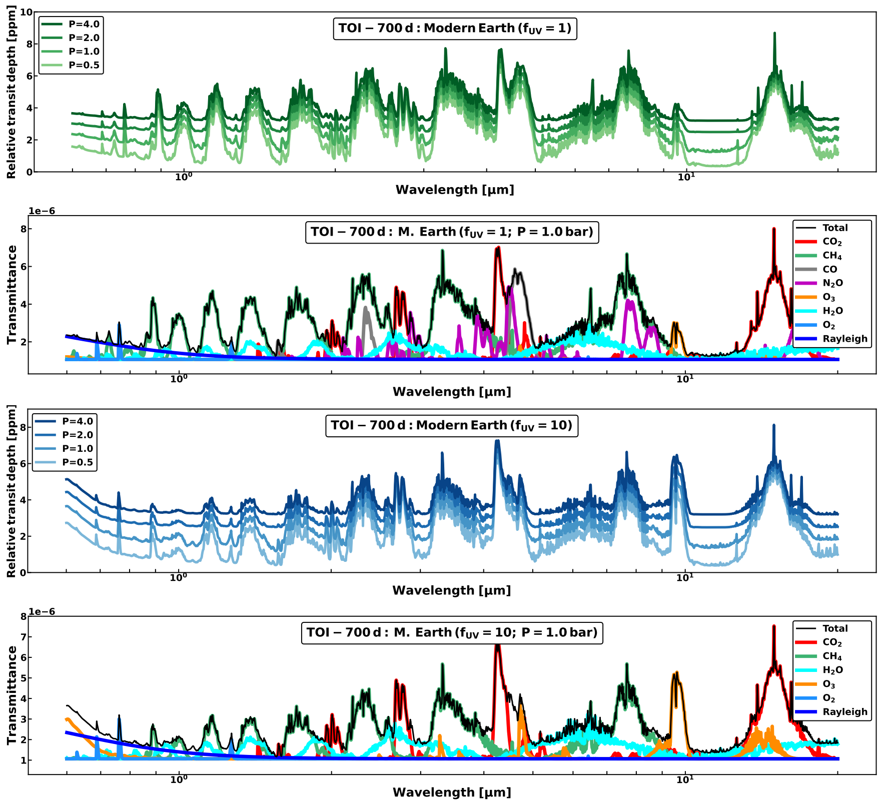

Figure 5. Same as Fig. 4, but for modern Earth-like atmospheres. The high-UV case shows stronger ozone features and a steeper short-wavelength slope.