THE PALE ORANGE DOT: SPECTRA AND CLIMATES OF HAZY ARCHEAN EARTHLIKE WORLDS.

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Introduction: The dimmer young sun still presents paradoxes for simulations of a clement Archean climate. Suggestions that the planet had a lower atmospheric pressure [1,2] and a periodically haze-rich atmosphere [3-7] present additional challenges to the reconstruction of a habitable climate. Here, we present 1D photochemical-climate simulations of Archean Earth with fractal hydrocarbon hazes that are consistent with geochemical data and account, for the first time, for the lower end of paleopressure estimates (0.5 bar). We find that haze affects climate, spectra, and has potential biological impact.

Climate: Our simulations show the globally averaged Archean Earth with a fractal hydrocarbon haze could have remained above 273 K for $CH_4/CO_2 < 0.2$. This is true even for a surface atmospheric pressure half of today's. We note 273 K is not a hard limit for planetary habitability because planets with surface temperatures of 260 K have been shown to have stable open ocean fractions of ~50% [8]. Thus, even thicker hazes may not preclude habitability.

Spectra: We also present the first simulated spectra of fractal hydrocarbon haze-rich Archean Earth as an analog for habitable, low-O_2 exoplanets that could be observed with a future space-based telescope mission. The hazes associated with these self-consistent solutions produce strong features for both direct imaging and transit spectroscopy missions. In direct imaging, a strong, broadband absorption feature is seen at short wavelengths, which "reddens" the color of the planet and could be remotely detectable at low spectral resolution (panel A of figure 1). In transit transmission, a sloped spectrum similar to Titan's [9] is seen that masks absorption features from gases at high haze thicknesses (panel B of figure 1).

Other Stellar Types: We examined how the stellar spectral energy distribution affects hydrocarbon haze formation for plants orbiting several stellar types: the flaring M3.5 dwarf AD Leo, a modeled quiescent M dwarf, a K2V star, and an F2V star. The stellar spectral energy distributions were scaled to produce the same total flux as the 2.7 Ga solar constant (0.8 × 1360 W/m^2, the modern solar constant). We find that planets with very high UV flux (the F2V dwarf) or very low UV flux (the quiescent M dwarf) do not form hazes in the atmospheres we test. At $CH_4/CO_2 = 0.2$, the hazes around the K2V and AD Leo planets reach maximum particle radii of 0.05 μm and 0.017 μm, respectively, compared to 0.5 μm for Archean Earth.

Biological Impact: Hazes strongly absorb at short wavelengths, providing a UV shield for the pre-ozone planet. The total surface-incident UV ($\lambda < 0.4$ μm) flux for a planet with a thick haze is reduced to only 16% of the incident flux for a planet with no haze and no ozone. UVC radiation ($\lambda = 0.20 - 0.28$ μm) is highly damaging to biology and is blocked by ozone on the modern Earth. The flux of UVC incident on the surface of a planet with haze is only 3% the incident UVC flux on a planet with no haze and no ozone. This flux, 0.026 W/m^2, can allow modest growth of cultures of *Chloroflexus aurantiacus*, an anoxygenic thermophilic phototroph [10].

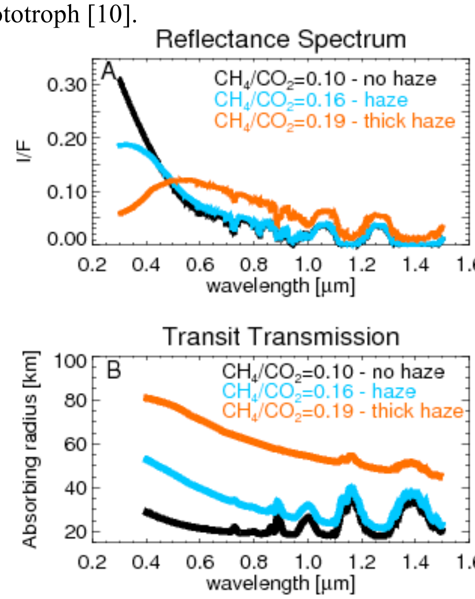

Figure 1 Hazes strongly affect direct beam and transit transmission planetary spectra.

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