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Modeling Venus' geochemical-climate evolution to assess habitability prospects for rocky planets near the inner edge of the habitable zone

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Understanding the coupled geochemical-climate evolution of terrestrial planets is crucial for anticipating their long-term habitability. Venus provides a unique opportunity to study what factors control habitability, as it is unknown whether early Venus was temperate when the young Sun was dimmer, despite seemingly having formed from comparable materials and at a similar orbital separation as Earth. Characterizing Venus' evolution is also important to exoplanetary research, as it may represent a large population of Earth-sized exoplanets orbiting near the inner edge of the habitable zone, and therefore constrain the prevalence and longevity of habitable environments in the universe.

The redox state of the post-accretion magma ocean has a strong control on atmospheric composition, and thus climate, of rocky planets. Classical magma ocean models assume Earth and Venus formed with oxidized (~log(fO2) = IW + 4) magma ocean conditions, which would produce H2O+CO2 dominated atmospheres. For Venus, a steam-rich early atmosphere is challenging to reconcile with habitability. However, recent work has proposed that Earth's magma ocean was more reduced (~log(fO2) = IW + 0.5) and would have thus produced a CO and H2-rich early atmosphere [1], with a similar expectation for early Venus. Since CO is a poorer greenhouse gas than CO2, there are potential habitability implications for such atmospheres in the context of early Venus.

Here, we present the results of investigating Venus' past with a fully coupled magma ocean, redox, fractionating atmospheric escape, and climate evolution model for terrestrial planets. The model can self-consistently accommodate arbitrary atmospheric compositions of H2O, CO2, CO, CH4, H2, and O2 and thereby capture the transition from H2-rich nebular atmospheres to high mean molecular weight secondary atmospheres (Figure 1). Preliminary results suggest that early Venus habitability is challenging to produce under clear sky conditions for any redox state, and likely would have required significant aerosol coverage via dayside water clouds or photochemical hazes. We also apply these calculations to inner edge rocky exoplanets to more fully characterize their habitability prospects as a function of mantle redox state and orbital separation.

[1] Sossi et al. (2020), Sci. Adv. 6, eabd1387.

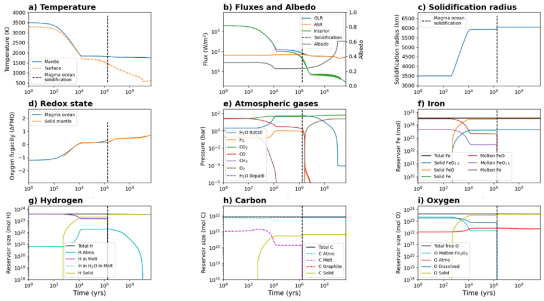

Figure 1. Time evolution example: PACMAN-P model applied to Venus's evolution showing a slightly reducing CO-CO_2 dominated initial atmosphere, where the vertical black dashed line indicates magma ocean solidification. Subplots: a) mantle and surface temperatures; b) outgoing longwave radiation (OLR), absorbed shortwave radiation (ASR), interior heat flux, and clear-sky Bond albedo calculated based on atmospheric composition; c) mantle solidification radius; d) oxygen fugacity as log(ΔFMQ); e) pressure of atmospheric gases; f) iron reservoirs partitioned between solid and molten; g) hydrogen stored in atmosphere, melt, as H_2O in melt, and solid mantle; h) carbon stored in atmosphere, melt, as graphite, and solid mantle; and i) oxygen stored in atmosphere, dissolved in melt, as molten ferric oxide, and solid mantle.