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Interpreting exoplanet biosignatures with a coupled atmosphere-interior-geochemical evolution model

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The atmospheric evolution of rocky planets is shaped by a range of astrophysical, geophysical, and geochemical processes. Interpreting observations of potentially habitable exoplanets will require an improved understanding of how these competing influences interact on long timescales. In particular, the interpretation of biosignature gases, such as oxygen, is contingent upon understanding the probable redox evolution of lifeless worlds. Here, we develop a generalized model of terrestrial planet atmospheric evolution to anticipate and interpret future observations of habitable worlds. The model connects early magma ocean evolution to subsequent, temperate geochemical cycling. The thermal evolution of the interior, cycling of carbon-hydrogen-oxygen bearing volatiles, surface climate, crustal production, and atmospheric escape are explicitly coupled throughout this evolution. The redox evolution of the atmosphere is controlled by net planetary oxidation via the escape of hydrogen to space, the loss of atmospheric oxygen to the magma ocean, and oxygen consumption via crustal sinks such as outgassing of reduced species, serpentinization reactions, and direct “dry” oxidation of fresh crust.

The model can successfully reproduce the atmospheric evolution of a lifeless Earth: it consistently predicts an anoxic atmosphere and temperate surface conditions after 4.5 Gyrs of evolution. This result is insensitive to model uncertainties such as the details of atmospheric escape, mantle convection parameterizations, initial radiogenic inventories, mantle redox, the efficiency of crustal oxygen sinks, and unknown carbon cycle and deep-water cycle parameters. This suggests abundant oxygen is a reliable biosignature for literal Earth twins, defined as Earth-sized planets at 1 AU around sunlike stars with 1-10 Earth oceans and less initial carbon dioxide than water.

However, if initial volatile inventories are permitted to vary outside these “Earth-like” ranges, then dramatically different redox evolution trajectories are permitted. We identify three scenarios whereby Earth-sized planets in the habitable zones of sunlike stars could accumulate oxygen rich atmospheres (0.01 - 10 bar) in the absence of life. Specifically, (i) high initial CO_2:H_2O endowments, (ii), >50 Earth ocean water inventories, or (iii) extremely volatile poor initial inventories, could all result in oxygen-rich atmospheres after 4.5 Gyrs of evolution. These false positives arise despite the assumption that there is always sufficient non-condensible atmospheric gases, N_2, to maintain an effective cold trap. Fortunately, all three oxygen false positive scenarios could potentially be

identified by thorough characterization of the planetary context, such as from using time resolved photometry to constrain surface water inventories.

The model also sheds light on the atmospheric evolution of Venus and Venus-like exoplanets. We can successfully recover the modern state of Venus' atmosphere, including a dense CO_2-dominated atmosphere with negligible water vapor and molecular oxygen. Moreover, there is a clear dichotomy in the evolutionary scenarios that recover modern Venus conditions, one in which Venus was never habitable and perpetually in runaway greenhouse since formation, and another whereby Venus experienced ~1-2 Gyr of surface habitability with a ~100 m deep ocean. We explore the likelihood of each scenario and suggest future in situ observations that could help discriminate between these two alternative histories.