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Are O_2-rich atmospheres a common outcome of lifeless planetary evolution?

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Abundant atmospheric O_2 is uniquely associated with photosynthesis in the Solar System, motivating its use as an exoplanet biosignature. However, oxygen is cosmically abundant, and planetary redox evolution may often favor atmospheric O_2 accumulation if abiotic sources of oxygen (H escape) overwhelm crustal sinks. If O_2-rich atmospheres are a common outcome of lifeless planetary evolution, then recognizing biospheres on exoplanets may become more challenging as contextual clues will be needed to disentangle O_2 biosignatures from abiotic "false positives". Here, we assess the likelihood of abiotic O_2 accumulation across stellar and planetary environments.

For planets orbiting M-dwarf stars, abiotic O_2 build-up appears plausible. During the extended pre-main sequence phase of M-dwarfs, intense XUV irradiation drives hydrodynamic escape whereby H is preferentially lost compared to O, potentially leaving behind hundreds of bars of O_2. This O_2 source could overwhelm crustal sinks, resulting in persistent O_2 atmospheres. While there are tentative observational hints that such planets may exist, many M-dwarf hosted rocky planets have seemingly lost their atmospheres entirely, thus avoiding O_2 biosignature "false positives".

For planets around sun-like stars, the surface redox balance is more challenging to predict because abiotic O_2 sources are weaker. The most plausible scenarios for abiotic O_2 accumulation on habitable planets around sun-like stars include (i) low non-condensable (N_2/CO_2) inventories weaking the cold trap leading to elevated H escape, (ii) deep surface oceans suppressing crustal O_2 sinks, and (iii) arid rocky planets whereby carbon cycle imbalances result in runaway warming and elevated H escape. Fortunately, models of atmosphere-interior evolution suggest that crustal O_2 sinks will typically overwhelm sources (Scenarios (i) and (iii)), and that where abiotic O_2 persists, its non-biological origin will be recognizable via reflected light observations (Scenario (ii)).

Terrestrial planets near the inner edge of the habitable zone (Venus and its exo-analogs) provide a critical testbed for understanding redox evolution. Despite likely past water loss, Venus lacks significant O_2 today, presumably due to crustal sinks. We combine atmosphere-interior evolution modeling with high P–T experiments of crustal oxidation kinetics to better understand Venus' redox evolution and make testable predictions for the atmospheres of rocky exoplanets.