Redox evolution via gravitational differentiation on rocky planets: implications for abiotic oxygen, water loss and habitability

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The oxidation of rocky planet surfaces and atmospheres, which arises from the twin forces of stellar nucleosynthesis and gravitational differentiation, is a universal process of key importance to habitability and exoplanet biosignature detection. Here we take a generalized approach to this phenomenon. Using a single parameter to describe redox state, we model the evolution of terrestrial planets both in the Solar System and outside it. Our model couples all the processes most critical to long-term redox evolution, including atmospheric photochemistry, diffusion and escape, line-by-line climate calculations and interior thermodynamics and chemistry. Our approach allows the self-consistent calculation of a planet's atmospheric and mantle redox state as a function of time and hence the identification of circumstances under which either transient or permanent buildup of abiotic oxygen (O_2) in a planet's atmosphere occurs. In most cases we find abiotic atmospheric O_2 buildup around M-stars during the pre-main sequence phase to be much less than calculated previously, because the planet's magma ocean absorbs most oxygen liberated from H_2O photolysis. However, loss of non-condensing atmospheric gases after the mantle solidifies remains a significant potential route to abiotic atmospheric O_2 subsequently. In all cases we predict that exoplanets that receive lower stellar fluxes, such as LHS1140b and TRAPPIST-1f and g, have the lowest probability of abiotic O_2 buildup and hence are the best targets for future biosignature searches. Key remaining uncertainties can be minimized in future by comparing our predictions for the atmospheres of hot, sterile exoplanets such as GJ1132b and TRAPPIST-1b and -c with observations.