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The case for secondary atmospheres on temperate rocky planets around M-dwarfs

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Early James Webb Space Telescope (JWST) observations of hot rocky exoplanets have revealed that many of these objects may be airless rocks. For example, JWST observations of TRAPPIST-1b [1] and c [2] disfavor substantial atmospheres containing CO_2. Given the similar densities of all TRAPPIST-1 planets, and the theoretical potential for atmospheric erosion around late M-dwarfs, this observation might be assumed to imply atmospheres are also unlikely for the outer planets. Here, we present a new, self-consistent model of atmosphere-interior evolution during the transition from primary to secondary atmospheres to show that this may not be the case. The model incorporates all Fe-C-O-H-bearing species and simulates magma ocean solidification, radiative-convective climate, thermal escape, and mantle redox evolution. For our illustrative example TRAPPIST-1, our model strongly favors atmosphere retention for the habitable zone planet TRAPPIST-1e. In contrast, the same model predicts a comparatively thin atmosphere for the Venus-analog TRAPPIST-1b, which would be vulnerable to complete erosion via non-thermal escape and is consistent with JWST observations. This difference arises because the duration of hydrodynamic escape on planets exterior to the runaway greenhouse limit is limited, and because surface water inventories are readily replenished by the reduction of FeO by H_2. More broadly, we suggest that habitable zone planets around M-dwarfs such as TRAPPIST-1 are highly likely to retain secondary atmospheres across a broad swath of initial compositions, a prediction that is seemingly supported by tentative atmospheric detections on other comparatively temperate rocky planets.

[1] Greene, T. P., et al. (2023). Nature, 618(7963), 39-42.
[2] Zieba, S., et al. (2023). Nature, 1-4.