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Hydrogen-Rich Exoplanet Atmospheres as Products of Water-Rock Reactions Modified by Stellar-Driven Escape

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Environments where liquid water is in physical contact with rocks initiate water-rock interaction that modifies mineral assemblages, fluid composition, and redox state. A fundamental product of these reactions is molecular hydrogen (H_2) generated through oxidation of reduced forms of iron, sulfur, carbon, and other elements. On Earth, the H_2 produced sustains subsurface microbial ecosystems and drives abiotic organic synthesis.

Recent observations by the James Webb Space Telescope have revealed exoplanets with an atmospheric signature of water vapor and low mean molecular weight envelopes consistent with hydrogen-rich atmospheres. Hydrogen-rich atmospheres on such planets are commonly interpreted as remnants of primordial nebular capture. However, stellar activity simultaneously drives atmospheric escape that can efficiently remove hydrogen over time. The extent to which secondary hydrogen production can compete with stellar-driven loss at the planetary scale remains relatively unconstrained.

We conducted equilibrium geochemical calculations for granitic, basaltic, and ultramafic lithologies across 350 temperature conditions and 93 water-rock mass ratios, spanning planetary water inventories from 1 to 93 wt% relative to Earth's crustal mass. Dissolved hydrogen production was scaled to global crust-ocean interactions and used as lower-boundary conditions for atmospheric structure and escape models.

Hydrogen yield increases systematically with temperature, water inventory, and lithology. In ultramafic-water scenarios, integrated H_2 release reaches ~9 x10^{18}kg, exceeding the mass of Earth's present-day atmosphere. Coupled hydrostatic structure and energy-limited escape calculations under sustained, flare-driven extreme ultraviolet (XUV) irradiation show that such hydrogen-rich atmospheres decay gradually rather than catastrophically: an initial ~9 x10^{18}kg H_2 inventory requires ~1.5 Gyr to erode to ~0.01% of Earth's present-day atmospheric mass. These timescales indicate that geochemically generated hydrogen can remain atmospherically significant on gigayear timescales despite ongoing stellar-driven escape.

These results demonstrate that water-rock interaction alone can generate atmospherically significant and geologically persistent hydrogen reservoirs without requiring primordial inheritance. Detection of H_2 in temperate exoplanet atmospheres may therefore reflect sustained interior redox processes operating in competition with stellar-driven escape. Because hydrogen production is intrinsically linked to the generation of chemical disequilibria, hydrogen-rich secondary atmospheres could represent observable manifestations of interior processes capable of sustaining habitable conditions.