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Magma Ocean–Atmosphere Interactions Reshape Atmospheric Signatures in Super-Earths and Sub-Neptunes

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Atmospheric compositions of sub-Neptunes and super-Earths are often interpreted as tracers of formation location relative to volatile ice lines. However, prolonged magma ocean phases enable chemical equilibration between a molten silicate reservoir, a metallic phase, and the overlying H–He envelope, potentially modifying primordial disk signatures.

We couple a synthetic population of about 1200 sub-Neptunes and super-Earths from the Bern Generation III formation model to an extended global chemical equilibrium framework including silicate and C–H–N–S chemistry. We compare accreted atmospheric compositions to chemically equilibrated atmospheres for planets formed inside and outside the water ice line.

We find that interior–atmosphere equilibration systematically redistributes volatile elements between envelope and interior, leading to shifts in atmospheric composition. The atmospheric C/O ratio deviates from the accreted state and remains systematically higher for planets formed beyond the ice line. Nitrogen is efficiently depleted through dissolution into the silicate melt, strongly reducing NH_3 and N_2, while HCN is produced under reducing conditions, resulting in generally low atmospheric nitrogen abundances.

In contrast, sulfur behaves differently. Although accreted H_2S partitions into the interior during equilibration, reducing its atmospheric abundance and generating minor SO_2, bulk atmospheric sulfur shows only weak dependence on formation location and remains more abundant than nitrogen-bearing species.

Silicon-bearing gases (SiH_4, SiO) are produced in substantial abundances consistent with metal–silicate redox exchange in hydrogen-rich conditions. Their distributions are narrower for planets formed outside the ice line, indicating tighter coupling between bulk composition and interior processing. More broadly, equilibration increases atmospheric metallicities for planets formed inside the ice line and reduces total envelope mass fractions through volatile partitioning.

These systematic trends provide a framework to link observed atmospheric compositions to planetary formation regions. In particular, the elevated C/O ratios and volatile patterns predicted for planets formed beyond the water ice line are consistent with current JWST observations of sub-Neptunes such as K2-18 b and TOI-270 d. Coupled interior–atmosphere evolution should therefore be accounted for when analyzing JWST and future Ariel spectra to infer the formation histories of super-Earths and sub-Neptunes.