Atmospheric retention in water-cooled sub-Neptunes

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It is known that the planetary radius population consists of super-Earths and sub-Neptunes separated by a valley at ~1.7R_{Earth} (e.g., Fulton et al., 2017). Theoretical studies suggest that sub-Neptunes can lose their envelopes and evolve into super-Earths by hydrodynamic escape, driven by heating of the upper atmosphere through X-ray and UV absorption (e.g., Owen and Wu, 2017). Whether sub-Neptunes can retain their thick, H2-dominated atmospheres depends on various factors. Among these, atmospheric composition is expected to play a crucial role, as radiatively active molecules such as H2O can lose heating energy through thermal emission, thereby reducing escape efficiency. However, the influence of atmospheric composition on the evolutionary pathways of sub-Neptunes remains insufficiently explored.

In this study, we applied a 1-D hydrodynamic escape model that incorporates chemical and radiative processes to sub-Neptunes' atmospheres composed of H2 and H2O. We calculated atmospheric escape rates as functions of stellar EUV flux, planetary gravitational acceleration, and H2O/H2 ratio at the base of the flow. Using these rates, we evolved sub-Neptunes with a fixed planetary mass and on circular orbits around an M2-type (0.45M_{sun}) star. We adopted Mp of 2.5 and 5M_{Earth}, initial envelope mass fractions of 1–5%, basal H2O/H2 ratio of 0-0.1, and semi-major axes of 0.01–0.3 au, corresponding to main-sequence stellar irradiance of 0.3–250 times the current terrestrial value. Chemical reactions involving H2, H2O, and their chemical products are considered. Heating by absorption of stellar X-rays and UV absorption is calculated using a reconstruction of the 0.1–280 nm spectrum of GJ 832 as a representative M2 dwarf. Radiative cooling by thermal line emission from H2O, OH, H3+, OH+, and H3O+ are also considered.

The atmospheric escape rate decreases as the basal H2O/H2 ratio increases primarily due to the radiative cooling effect of H2O, regardless of gravity and EUV flux. It becomes about one order of magnitude low at a basal H2O/H2 ratio of ~0.1 relative to a pure H2 atmosphere. Consequently, variations in the atmospheric H2O/H2 ratio play a crucial role in determining whether sub-Neptunes can retain their atmospheres over several Gyr. These results suggest that H2O condensation in the lower atmospheres of temperate sub-Neptunes could explain the paradoxical observations that these objects disappear more rapidly than their counterparts closer to the star.

Keywords: sub-Neptune, atmospheric evolution, atmospheric escape

