



Most Super-Earths Have Less Than 3% Water

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Abstract

Super-Earths are highly irradiated, small planets with bulk densities approximately consistent with Earth. We construct combined interior atmosphere models of super-Earths that trace the partitioning of water throughout a planet, including an iron-rich core, silicate-rich mantle, and steam atmosphere. We compare these models with exoplanet observations to infer a 1σ upper limit on the total water mass fraction of $\lesssim 3\%$ at the population level. We consider end-member scenarios that may change this value, including the efficiency of mantle outgassing, escape of high mean molecular weight atmospheres, and increased iron core mass fractions. Although our constraints are agnostic as to the origin of water, we show that our upper limits are consistent with its production via chemical reactions of primordial hydrogen-dominated atmospheres with magma oceans. This mechanism has also been hypothesised to explain Earth's water content, possibly pointing to a unified channel for the origins of water on small terrestrial planets.

Unified Astronomy Thesaurus concepts: [Exoplanet structure \(495\)](#); [Exoplanets \(498\)](#); [Exoplanet formation \(492\)](#); [Exoplanet evolution \(491\)](#)

1. Introduction

Super-Earths offer a unique insight into planet formation. With orbital periods $\lesssim 100$ days and sizes $\lesssim 1.8 R_{\oplus}$, super-Earths are among the most common class of planet in our Galaxy (e.g., A. W. Howard et al. 2012; F. Fressin et al. 2013; E. A. Petigura et al. 2013; G. D. Mulders et al. 2015; J. K. Zink et al. 2023). Precise mass and radius measurements have revealed their bulk densities to be “Earth-like” (e.g., Y. Wu & Y. Lithwick 2013; L. M. Weiss & G. W. Marcy 2014; L. A. Rogers 2015; A. Wolfgang et al. 2016; J. Chen & D. Kipping 2017), prompting questions as to whether Earth's interior composition is a natural outcome of planet formation.

Perhaps the most convenient definition of super-Earths is that they sit below the radius valley. The radius valley is an observed paucity in planet occurrence at $\sim 1.8 R_{\oplus}$, although its exact location varies with orbital period and stellar mass (e.g., B. J. Fulton et al. 2017; E. A. Petigura et al. 2018; V. Van Eylen et al. 2018; E. A. Petigura et al. 2022; C. S. K. Ho & V. Van Eylen 2023). Above the radius valley sits the population of sub-Neptunes, whose bulk density is markedly reduced when compared to super-Earths. Inferring the composition of sub-Neptunes is fraught with degeneracy (e.g., L. A. Rogers 2015; J. L. Bean et al. 2021; J. G. Rogers et al. 2023). This arises since there are expected to be four major chemical reservoirs within a sub-Neptune: iron, silicates, H_2O -dominated volatiles, and hydrogen. While it is known that a significant hydrogen mass fraction is required to reproduce the densities of the largest sub-Neptunes (e.g., D. Jontof-Hutter et al. 2016), attempting to constrain the mass fractions of each reservoir when only utilizing two observables, being planetary mass and size, is an underconstrained mathematical problem.

To alleviate some of the degeneracy of sub-Neptune composition, one can utilize planet structure and evolution models. However, different models currently predict different interior compositions. On the one hand, models of atmospheric evolution including escape, suggest that super-Earths and sub-Neptunes formed from the same underlying planet population of hydrogen-dominated atmospheres atop Earth-like interiors (e.g., E. D. Lopez & J. J. Fortney 2013; J. E. Owen & Y. Wu 2013; S. Ginzburg et al. 2018; A. Gupta & H. E. Schlichting 2019; J. G. Rogers & J. E. Owen 2021). On the other hand, planet population-synthesis models predict a prominent population of water worlds, defined as planets with a water mass fraction of several tens of percent (e.g., C. Mordasini et al. 2009; J. Venturini et al. 2016; S. N. Raymond et al. 2018; L. Zeng et al. 2019; O. Mousis et al. 2020; R. Burn et al. 2024), arising due to formation beyond the water–ice line, followed by large-scale migration (e.g., K. Lodders 2003; B. Bitsch et al. 2015; J. Venturini et al. 2020; N. Brügger et al. 2020).

Perhaps the most promising avenue for breaking compositional degeneracy is with models of planet structure and chemical composition. For example, the requirement of hydrostatic and chemical equilibrium provides more stringent constraints on the possible outcomes of planet formation (e.g., H. E. Schlichting & E. D. Young 2022; E. D. Young et al. 2023; J. G. Rogers et al. 2024b). Future atmospheric characterization of sub-Neptune atmospheres may inform these models (see B. Benneke et al. 2024), although for now, our knowledge of sub-Neptune compositions remains uncertain.

Super-Earths, on the other hand, provide a simpler chemical system to solve. What is clear for planets existing below the radius valley is that it is challenging to explain the existence of a significant, long-lived hydrogen-dominated atmosphere. Their notably higher bulk densities provide observational evidence that they do not host large hydrogen atmospheres, which is reinforced by theoretical insights into atmospheric escape under intense stellar irradiation (e.g., J. E. Owen & A. P. Jackson 2012; D. Kubyskhina et al. 2018; A. Caldiroli et al. 2022; M. Schulik & R. Booth 2023).



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In short, planets below the radius valley are typically smaller in mass and experience higher equilibrium temperatures, meaning that they are very unlikely to host a hydrogen-dominated atmosphere if indeed they ever had one (see also E. J. Lee et al. 2022; J. G. Rogers et al. 2024a).

From the original list of four chemical reservoirs for sub-Neptunes, the lack of atmospheric hydrogen for super-Earths reduces the list to three major chemical components: iron, silicates, and H_2O -dominated volatiles. For observed mass and radius, this still yields an underconstrained problem. However, it allows one to explore parameter space in a more straightforward manner.

In this study, we focus on the water content of super-Earths. Water is evidently of major interest for habitability, however, it is also important in the context of understanding planet formation and evolution. Formation scenarios resulting in several tens of percent in water mass fraction clearly require delivery of water from ice-rich pebbles or planetesimals formed beyond the ice line (e.g., C. Mordasini et al. 2009; S. N. Raymond et al. 2018). However, recent studies have shown that water can be endogenously produced as a result of the chemical equilibration of hydrogen-dominated atmospheres and magma oceans (e.g., E. S. Kite & L. Schaefer 2021; H. E. Schlichting & E. D. Young 2022). The total water mass fraction produced through this mechanism is typically of order a few percent (H. E. Schlichting & E. D. Young 2022; J. G. Rogers et al. 2024b). A similar debate exists for the origins of water on Earth, either delivered (e.g., S. N. Raymond et al. 2004, 2009) or chemically produced (e.g., J. Wu et al. 2018; E. D. Young et al. 2023).

In this study, we constrain the water content of super-Earths by constructing simple physical and chemical models that account for the partitioning of water between a planet's metal core, silicate mantle, and atmosphere. We compare these models with observed planetary masses and radii in order to place upper limits on water mass fractions at the population level. Crucially, we are agnostic as to the origin of the water, i.e., whether it was delivered or endogenously produced. We also explore processes that may change our statistical constraints, including atmospheric escape of high mean molecular weight atmospheres and mantle outgassing. For a given water mass fraction, these scenarios can change the bulk density of a super-Earth and hence must be included when performing this analysis.

We simplify the problem by choosing to model planets with an Earth-like iron mass fraction, which is supported by various lines of evidence, including V. Adibekyan et al. (2021), who showed that the majority of super-Earths have iron mass fractions consistent with, or less than that of Earth. Other lines of evidence in favor of Earth-like interior compositions come from spectroscopic observations of polluted white dwarfs (e.g., A. E. Doyle et al. 2020; I. L. Trierweiler et al. 2023; L. K. Rogers et al. 2024c) and broadband transit photometry of catastrophically evaporating rocky planets (B. Campos Estrada et al. 2024). In this initial study, we also choose to construct a simple chemical system which ignores carbon-, nitrogen-, and sulfur-bearing species since these are unlikely to contribute a significant fraction of a planet's overall mass budget.

Our paper is structured as follows: in Section 2, we present a model for super-Earth interiors (Section 2.1) and atmospheres (Section 2.2). We discuss our end-member scenarios, including the effects of atmospheric escape and mantle outgassing in Section 2.3, with results presented in Section 2.4. In Section 3,

we apply these models to infer upper limits on water mass fractions of the observed super-Earth population. We discuss data selection (Section 3.1) and our statistical methodology (Section 3.2), with results presented in Section 3.3. Discussion and conclusions are included in Sections 4 and 5, respectively.

2. A Model for Super-Earths

2.1. Interior Model

We employ an interior model from H. Luo et al. (2024), which is based on earlier versions of C. Dorn & T. Lichtenberg (2021) and C. Dorn et al. (2015). For this application, we focus on rocky worlds with varying amounts of water content, parameterized by a water mass fraction, $X_{\text{H}_2\text{O}} \equiv M_{\text{H}_2\text{O}}/M_{\text{p}}$, where $M_{\text{H}_2\text{O}}$ is the total mass of water and M_{p} is the total planet mass. The water can be present in the metal core, the mantle, and the surface, depending on the specific thermal state of the planet. The main addition to the model compared to H. Luo et al. (2024) is the ability of the model to outgas water from the mantle. We describe more details in the following.

We consider a core made of Fe, H, and O. For solid Fe, we use the equations of state for hexagonal close packed iron (K. Hakim et al. 2018; F. Miozzi et al. 2020). For liquid iron with, and without H_2O , we use H. Luo et al. (2024). The core thermal profile is assumed to be adiabatic throughout the core. At the core–mantle boundary (CMB), there is a temperature jump as the core can be hotter than the mantle due to the residual heat released during core formation. We follow L. Stixrude (2014) and add a temperature jump at the CMB temperature such that the temperature at the top of the core is at least as high as the melting temperature of the silicates.

The mantle is assumed to be made up of three major constituents, i.e., MgO , SiO_2 , and FeO . For the solid mantle, we use the thermodynamical model `Perple_x` (J. A. D. Connolly 2009), to compute stable mineralogy and density for a given composition, pressure, and temperature, employing the database of L. Stixrude & C. Lithgow-Bertelloni (2022). For pressures higher than ~ 125 GPa, we define stable minerals a priori and use their respective equation of states from various sources (R. J. Hemley et al. 1992; R. A. Fischer et al. 2011; S. Faik et al. 2018; R. Musella et al. 2019). For the liquid mantle, we calculate its density assuming an ideal mixture of main components (Mg_2SiO_4 , SiO_2 , and FeO ; H. J. Melosh 2007; S. Faik et al. 2018; H. Ichikawa & T. Tsuchiya 2020; S. T. Stewart et al. 2020) and add them using the additive volume law. Note that we use Mg_2SiO_4 instead of MgO since the data for forsterite have been recently updated for the high-pressure temperature regime, which is not available for MgO to our knowledge. The mantle is assumed to be fully adiabatic.

Water can be added to the mantle melts, while the solid mantle is assumed to be dry. The addition of water reduces the density, for which we follow S. Bajgain et al. (2015) and decrease the melt density per weight percentage of water by 0.036 g cm^{-3} . For small water mass fractions, this reduction is nearly independent of pressure and temperature. The melting curve of mantle material is calculated for dry and pure MgSiO_3 to which the addition of water (R. F. Katz et al. 2003) and iron (C. Dorn et al. 2018a) can lower the melting temperature. Water within the core will also lower its melting temperature, for which we follow H. Luo et al. (2024). This water can also be in both liquid and solid phases. The partitioning between mantle melts and the water layer is determined by a modified Henry's law, for which we use the

fitted solubility function of C. Dorn & T. Lichtenberg (2021). For the partitioning of water between iron and silicates, we follow H. Luo et al. (2024). For the equilibration pressure of water to partition between iron and silicates, we use half of the CMB pressure, which is within typically discussed values for Earth (0.3–0.6). Varying this pressure would introduce overall small changes in the distribution of water.

Beyond the mantle, water can be in solid, supercritical, and gas phases. Whenever the water is in the gas (steam) phase, we use the description in Section 2.2 to calculate its extent and evolution. We also consider solid and supercritical water phases, which are calculated using the equation of state compilation in J. Haldemann et al. (2020).

2.2. Atmospheric Evolution Model

The models of H. Luo et al. (2024) prescribe the partitioning of water between the interior and atmosphere of a rocky super-Earth. The presence of water within the interior increases its radius due to its reduced density when compared to silicate rock and iron. Although most of the water is sequestered in the interior, the presence of a small steam atmosphere also increases the radius of a planet. However, it is imperative to consider the thermodynamic evolution of atmospheres since they will radiatively cool and contract, thus changing in size as a function of time. Furthermore, this evolution will depend on atmospheric composition due to varying opacities and mean molecular weights. To account for this, we build semianalytic radiative–convective models of steam atmospheres based on the equivalent case of hydrogen-dominated atmospheres used in J. E. Owen & Y. Wu (2017), A. Gupta & H. E. Schlichting (2019), J. G. Rogers & J. E. Owen (2021), W. Misener & H. E. Schlichting (2022), and J. G. Rogers et al. (2023). For the deep, convective interior, we assume an adiabatic density profile of the form:

$$\rho(r) = \rho_{\text{rcb}} \left[1 + \nabla_{\text{ad}} \frac{GM_p}{c_s^2 R_{\text{rcb}}} \left(\frac{R_{\text{rcb}}}{r} - 1 \right) \right]^{\frac{1}{\gamma-1}}, \quad (1)$$

where the subscript “rcb” refers to quantities evaluated at the radiative–convective boundary. Here, ρ is the density, γ is the adiabatic index, $\nabla_{\text{ad}} \equiv (\gamma - 1)/\gamma$ is the adiabatic temperature gradient, M_p is the planet’s mass, and R_{rcb} is the position of the radiative–convective boundary. Above the convective region sits a radiative layer, assumed to be isothermal at an equilibrium temperature of T_{eq} . The sound speed in Equation (1) is evaluated at the radiative–convective boundary, $c_s^2 \equiv k_B T_{\text{eq}} / \mu m_H$, where m_H is the mass of a hydrogen atom. For a steam-dominated atmosphere, we adopt a mean molecular weight of $\mu = 18$ and an adiabatic index of $\gamma = 1.33$ (see Appendix 1B of E. M. R. Kempton et al. 2023). Since most super-Earths exist at high equilibrium temperatures (particularly once accounting for survey biases; J. G. Rogers & J. E. Owen 2021), we evaluate models with $T_{\text{eq}} > 500$ K such that water is very unlikely to condense out of the gas phase within an atmosphere.

At each time step, we cool the model with a radiative luminosity given by:

$$L_{\text{rad}} = \frac{64\pi \nabla_{\text{ad}} GM_p \sigma T_{\text{eq}}^4}{3 c_s^2 \kappa_{\text{rcb}} \rho_{\text{rcb}}}, \quad (2)$$

where κ_{rcb} is the gas opacity evaluated at the radiative–convective boundary. Here we use the tabulated H₂O Rosseland mean

opacities from E. M. R. Kempton et al. (2023), which include Rayleigh scattering and molecular absorption. Once the new total energy of the system has been calculated, including thermal contributions from the rocky interior (see detailed description in W. Misener & H. E. Schlichting 2022), we solve for the new radiative–convective boundary radius R_{rcb} and density ρ_{rcb} for a given total planet mass and energy using `scipy.fsolve` (P. Virtanen et al. 2020). From there, we calculate the photospheric radius by finding the location within the radiative isothermal layer for which the optical depth to incoming radiation is $\tau = 2/3$. We evolve the system with an adaptive-step predictor–corrector ordinary differential equation solver. Note that we do not incorporate atmospheric escape in the evolution models at this stage, but instead consider end-member scenarios based on the retention of atmospheres, as discussed in Section 2.3.

For each model from Section 2.1, we evolve its atmosphere for 5 Gyr, being the typical age of observed super-Earths (e.g., T. A. Berger et al. 2020). We stress that the final size of planets after several gigayears of evolution is insensitive to the exact choice in planet age due to the convergent nature of thermodynamic cooling and contraction (e.g., J. G. Rogers et al. 2023). For initial conditions, we set the base of the atmosphere to be at 4000 K. Again, we highlight that the final size of planet atmospheres after a gigayear of evolution is insensitive to this value. We confirm a posteriori that these assumptions have a negligible effect on our conclusions by comparing calculations assuming different stellar ages of 1 Gyr and 10 Gyr, which yield a difference in the inferred water mass fraction of $<0.3\%$ (see Section 3.2). These simplifying assumptions would not hold when considering young planets, particularly for stellar ages $\lesssim 100$ Myr when atmospheric contraction can be significant. Since typical ages of Kepler and TESS planet hosts are >1 Gyr, we can safely ignore this consideration.

Figure 1 shows two example models of atmospheric evolution, highlighting the differences between H₂O steam and H₂ atmospheres in blue and orange, respectively. Both models are otherwise identical, with atmospheric mass fractions of 0.1%, interior masses of $4 M_{\oplus}$, interior radii of $1.44 R_{\oplus}$, with initial atmospheric base temperatures of 4000 K, orbiting solar-mass stars with equilibrium temperatures of 1000 K. For the H₂ atmosphere in Figure 1, we adopt a mean molecular weight of $\mu = 2.35$ (E. Anders & N. Grevesse 1989) and a Rosseland mean opacity scaling of:

$$\kappa = 1.29 \times 10^{-2} \left(\frac{P}{1 \text{ bar}} \right)^{\alpha} \left(\frac{T}{1000 \text{ K}} \right)^{\beta} \text{ cm}^2 \text{ g}^{-1}, \quad (3)$$

where $\alpha = 0.68$ and $\beta = 0.45$ (L. A. Rogers & S. Seager 2010; J. E. Owen & Y. Wu 2017). Figure 1 shows each planet’s size, including their photospheric and radiative–convective boundary radii as solid and dotted lines, respectively. The impact of the mean molecular weight is clear, with the H₂ model being significantly more inflated than the H₂O model (see similar results from E. D. Lopez 2017). After several gigayears of evolution, the radiative–convective boundaries of both planets converge on their interior (metal core + mantle) radii, suggesting an atmosphere that is almost entirely radiative. In this case, and given that both planets have the same surface gravity, the photospheric size of each planet is dependent on their atmospheric mean molecular weight and opacity. The Rosseland mean opacity for H₂O is

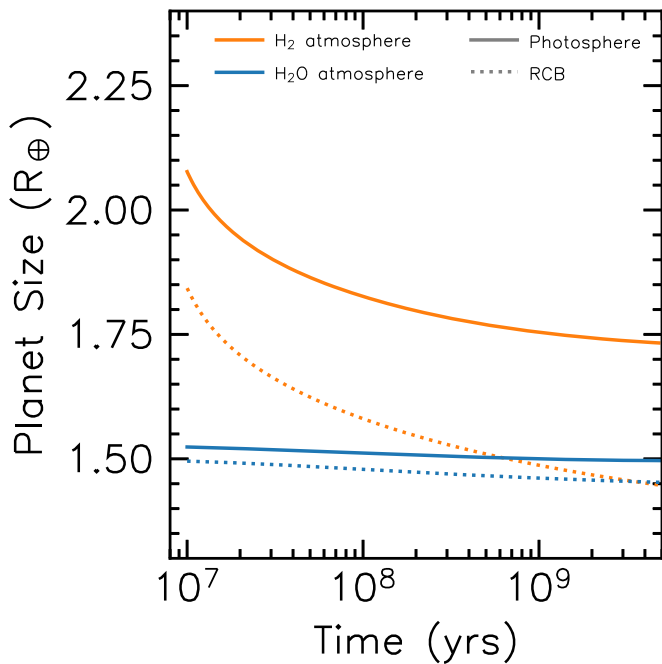


Figure 1. The atmospheric evolution for hydrogen and steam-dominated atmospheres. Each planet’s photospheric and radiative–convective boundary (“RCB”) radii are shown in solid and dotted lines, respectively. An H_2 -dominated atmosphere is shown in orange, and an H_2O -dominated atmosphere is shown in blue. Both planets are otherwise identical, with atmospheric mass fractions of 0.1%, initial atmosphere base temperatures of 4000 K, interior masses of $4 M_\oplus$, and equilibrium temperatures of 1000 K.

relatively high, particularly in the temperature regime of interest for highly irradiated super-Earths (E. M. R. Kempton et al. 2023). As such, even a small atmospheric mass fraction $\lesssim 10^{-3}$ can increase a planet’s radius by $\sim 10\%$, particularly for low-mass planets (see Section 2.3).

2.3. A Selection of Illustrative End-member Scenarios

Our goal is to constrain the water content of super-Earths (see Section 3). To do so, we consider the outcome of two end-member scenarios of planet formation and evolution that can conceivably alter a super-Earth’s size for a given mass.

First, atmospheric escape can alter the size of a super-Earth by removing a significant fraction of its atmosphere. The physics of mass loss for steam-dominated atmospheres and, more generally, high mean molecular weight atmospheres under high stellar irradiation is currently uncertain. To first order, one would expect a significant fraction of such thin atmospheres to hydrodynamically escape under extreme stellar irradiation. Under such conditions, escaping hydrogen (either molecular, photodissociated, or ionized) can also drag heavier molecular species (e.g., D. M. Hunten et al. 1987; E. Chassefière 1996; R. Luger & R. Barnes 2015). However, the drag efficiency is poorly understood due to its complex dependency on heating sources, e.g., bolometric or X-ray/extreme ultraviolet. Due to these unknowns, we do not explicitly include escape in our models but instead consider the two end-member scenarios, namely the case in which a steam atmosphere is completely retained and the other in which it is completely removed.

Second, another process which may alter the size of a super-Earth is outgassing. Sequestered volatiles, such as H_2O , reduce the density of interiors since they are much lighter than the background medium, e.g., rock or metal. This is often

parameterized as a density deficit. If significantly outgassed, however, the sequestered volatiles are released into the atmosphere. This increases the size of the atmosphere and slightly reduces the size of the interior, due to its increased density. We model the outgassed end-member by forcing the temperature at the top of the mantle to be just below the melting temperature such that the mantle is dry. At the same time, we calculate the amount of water hidden in the core from the equivalent model without outgassing, such that the core contains the maximum amount of water possible. Similar to atmospheric escape, the physics of outgassing on super-Earths is complex. Therefore, we again consider the two end-member scenarios: complete retention of volatiles within a planet’s silicate mantle and complete outgassing of volatiles. Note that we do not consider outgassing of volatiles stored in a super-Earth’s metal core, since these are very likely to be locked within the core due to inefficient transport from core to planetary surface over gigayear timescales.

As discussed, we choose to model super-Earths with an Earth-like iron mass fraction of 33%, due to multiple lines of supporting evidence at the population level (e.g., V. Adibekyan et al. 2021; I. L. Trierweiler et al. 2023; B. Campos Estrada et al. 2024). Nevertheless, changing the iron mass fraction can also alter a planet’s bulk density. We discuss this in Section 4.4.

2.4. Results: Super-Earth Models

We present our models in Figure 2, all evaluated at 5 Gyr and compared to exoplanet observations as described in Section 3.⁴ In the left-hand panels, we show the masses and radii of our planets under different scenarios. In the right-hand panels, we show the same models as a function of planet mass versus normalized density. This is the density a planet would have if it had the same mass as Earth. In other words, planets that are overdense when compared to Earth sit above 5.5 g cm^{-3} , and vice versa. For this calculation, we utilize the Earth-like grid of models from Section 2.1 with a 33% iron mass fraction and no water content. In the top row, we vary the water mass fraction of the planet from 0.01 to 0.10. This water content is partitioned throughout the planet, as described in Section 2.1, resulting in steam atmospheric mass fractions varying from $\sim 10^{-5}$ to $\sim 10^{-3}$, with the exact values varying with planet mass.

In the second row, we vary the planet’s equilibrium temperature. Atmospheres of a given mass and age at a higher equilibrium temperature are larger than those at lower temperatures. This is because gas densities in the upper radiative atmosphere are reduced, raising the photospheric radius.

In the third row, we demonstrate the effect of atmospheric retention or loss. Dotted–dashed triangles represent models for which the steam atmosphere has been completely removed. Note that models with no atmospheres do not contract to Earth-like densities since there is still a significant water content within each planet’s interior, resulting in density deficits when compared to Earth.

Finally, in the bottom row, we demonstrate the effect of mantle outgassing. This process pushes more water content into the atmosphere, increasing the typical atmospheric mass fractions to several percent, with the exact value varying with planet mass.

⁴ These models are made publicly available at doi:[10.5281/zenodo.14172976](https://doi.org/10.5281/zenodo.14172976).

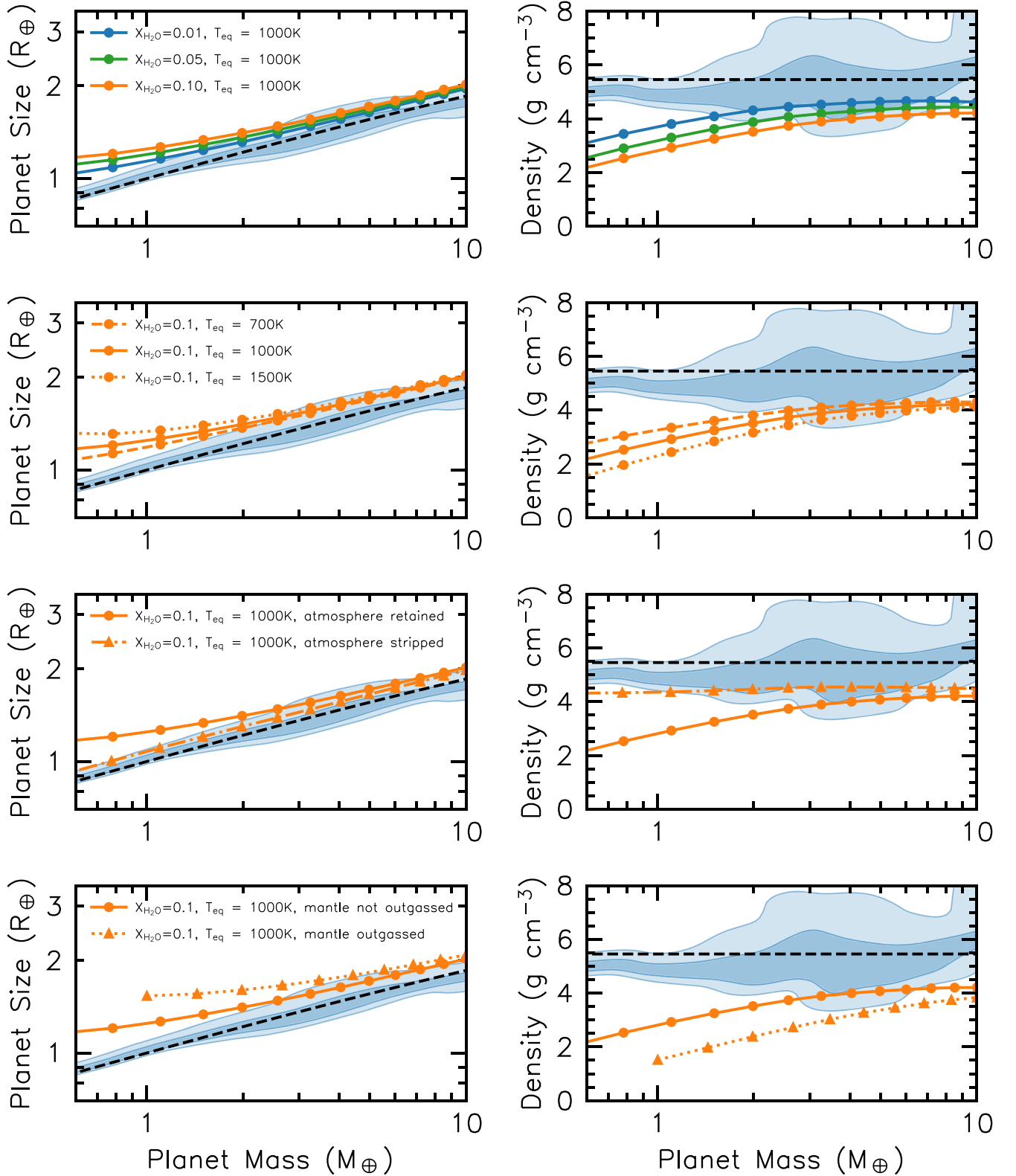


Figure 2. Super-Earth models are presented alongside the 1σ and 2σ contours of observed super-Earths (see Section 3.1 and Figure 4). In the left-hand column, we show this as a function of planet mass vs. radius, and in the right-hand column, we show this vs. normalized density. In the first row, we show three different total water mass fractions of 0.01, 0.05, and 0.10 in blue, green, and orange, respectively. In the second row, we vary the equilibrium temperature from 700 K, 1000 K, and 1500 K in dashed, solid, and dotted lines, respectively. In the third row, we show models with and without their atmospheres removed as triangles and circles, respectively. In the bottom row, we show models with and without their mantles outgassed in triangles and circles, respectively. Black dashed lines represent Earth-like with normalized densities $\approx 5.5 \text{ g cm}^{-3}$. These mass–radius relations are made publicly available at doi:[10.5281/zenodo.14172976](https://doi.org/10.5281/zenodo.14172976).

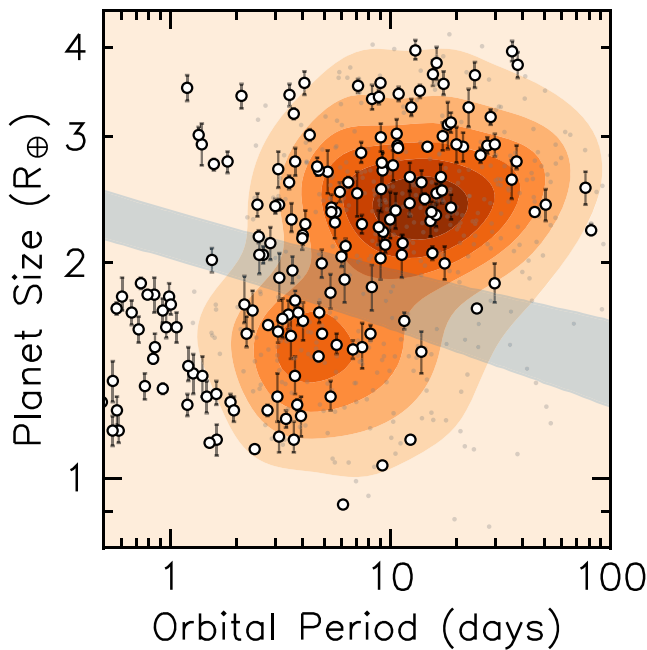


Figure 3. Our sample of planets from the PlanetS catalog (J. F. Otegi et al. 2020; L. Parc et al. 2024) is shown as white circles. We distinguish super-Earths from sub-Neptunes using the definition of the radius valley from C. S. K. Ho et al. (2024), which accounts for the radius dependence of the radius valley on orbital period and stellar mass. Orange contours and gray points show the underlying Kepler sample from C. S. K. Ho et al. (2024). The 1σ uncertainties on the radius valley are shown in blue, projected through the stellar mass axis.

3. On the Implications of Super-Earth Water Content

We now aim to place constraints on the water content of observed super-Earths, utilizing the models presented in Section 2. We perform this statistical inference under the scenarios presented in Section 2.3, since they are able to change the density of a super-Earth for a given water mass fraction (see Figure 2).

3.1. Sample Selection

For this analysis, we seek a high-fidelity sample of super-Earths with reliably measured masses and radii. We follow the procedure of J. G. Rogers et al. (2024b) in utilizing the PlanetS catalog (J. F. Otegi et al. 2020; L. Parc et al. 2024), which selects planets based on various reliability and accuracy conditions. Planets in this catalog have relative mass and radius uncertainties of less than 25% and 8%, respectively. Super-Earths are then defined to exist below the radius valley, as prescribed in C. S. K. Ho et al. (2024). We choose this latter definition of the valley due to its well-defined dependence on orbital period and stellar mass, and its derivation from precise short-cadence Kepler data. In Figure 3, we present our planet sample radii as a function of orbital period, with the radius valley boundaries projected through the stellar mass axis. We also present the C. S. K. Ho et al. (2024) Kepler sample as gray points and orange contours, from which our valley definition is derived. For full details on these data selection criteria, we point the reader to J. G. Rogers et al. (2024b). While it is possible to quantify biases for homogenous transit surveys such as Kepler, this is typically not possible for the samples including mass measurements such as PlanetS. This means

that our inferred water mass fractions are representative of the observed population instead of the underlying population.

In Figure 4, we present our sample of super-Earths alongside sub-Neptunes in gray for completeness. In the left-hand panel, we present planet masses and radii, colored by their equilibrium temperature (assuming zero albedo). In the right-hand panel, we show each planet's normalized density. Blue contours represent the 1σ and 2σ boundaries of the distribution of observed planets, calculated with a kernel density estimator and equal density in each slice in planet mass.

3.2. Statistical Methodology

Each set of scenario assumptions (i.e., atmospheric stripping and interior outgassing, see Section 2.3) provides a grid of planet models across our adopted parameter space, which spans $M_p \in [0.5, 10] M_\oplus$ and $X_{H_2O} \in [0.0, 0.4]$, all evaluated at 5 Gyr. These scenarios are then repeated for three different equilibrium temperature regimes: $T_{eq} \in \{700, 1000, 1500\}$ K. In general, the larger the water mass fraction, X_{H_2O} , the larger the planet of a given mass due to its inflated interior and more substantial atmosphere (if present). Similarly, the larger the equilibrium temperature, the larger the extent of the steam atmosphere due to decreased gas densities. For each observed super-Earth in our sample, we interpolate over the grid of models to find the water mass fraction reproducing the planet's measured density. In some scenarios, an observed planet may be denser than any of our models, implying an inferred water mass fraction of $X_{H_2O} = 0$ and possibly a higher iron mass fraction. In other cases, a planet may be less dense than any model, implying a water mass fraction that is greater than any in our grid. In the latter case, which occurs very infrequently, we draw a water mass fraction at random from a uniform distribution between the maximum value in our grid (typically ~ 0.4) and $X_{H_2O} = 1$. This is analogous to a uniform (uninformative) Bayesian posterior beyond the parameter space of our grid of models.

To account for uncertainties in the observed planet masses and radii, we iteratively resample with replacement from our population of super-Earths. For each iteration, we repeat the above procedure with the observed masses and radii resampled within their 1σ uncertainties. This sample is then reclassified into super-Earths and sub-Neptunes following Section 3.1, and water mass fractions are calculated as before. We repeat this 10,000 times for each scenario, yielding 10,000 measurements of water mass fraction for each super-Earth in our sample. We combine these measurements and quote the 1σ upper limits on the population-level water mass fraction. We repeat this for model grids at different equilibrium temperatures (700 K, 1000 K, and 1500 K) so as to investigate the impact of incident flux on inferred water mass fraction. Regardless of the physical scenario, the 1σ upper limit on water mass fraction equates to a lower limit on the normalized density of 4.81 g cm^{-3} for our sample of super-Earths.

3.3. Results: Super-Earth Water Content

Each modeled scenario yields a distribution of inferred water mass fractions for the population of observed super-Earths. An example can be seen in Figure 5. Here we show the cumulative distribution function (CDF) of inferred water mass fractions under the scenario of retained steam atmospheres around Earth-like interiors, with no outgassing at an equilibrium temperature of 1000 K. This CDF is shown with a linear and logarithmic scale on the left- and right-hand panel, respectively. One can see that the

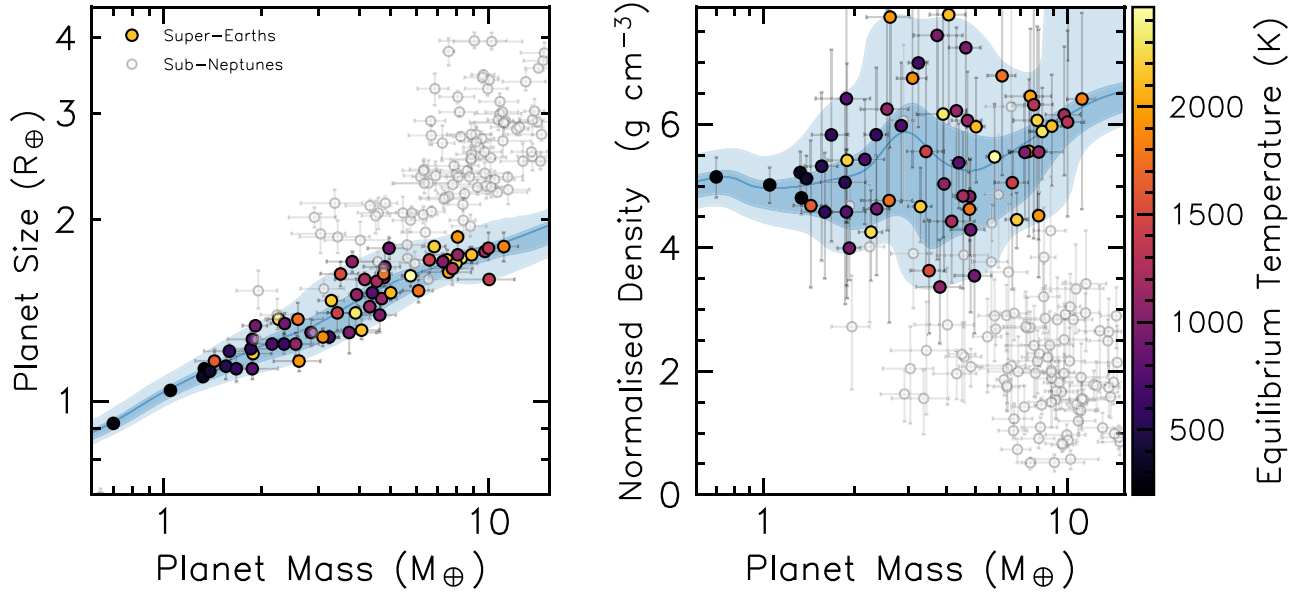


Figure 4. Our sample of super-Earths is shown as circles, colored by their equilibrium temperatures. Sub-Neptunes are shown in gray for completeness. Blue contours show the 1σ and 2σ bounds on the distribution of super-Earths as a function of planet mass vs. radius (left) and normalized density (right). This latter variable represents the density of each planet scaled to Earth, which has a density of $\approx 5.5 \text{ g cm}^{-3}$.

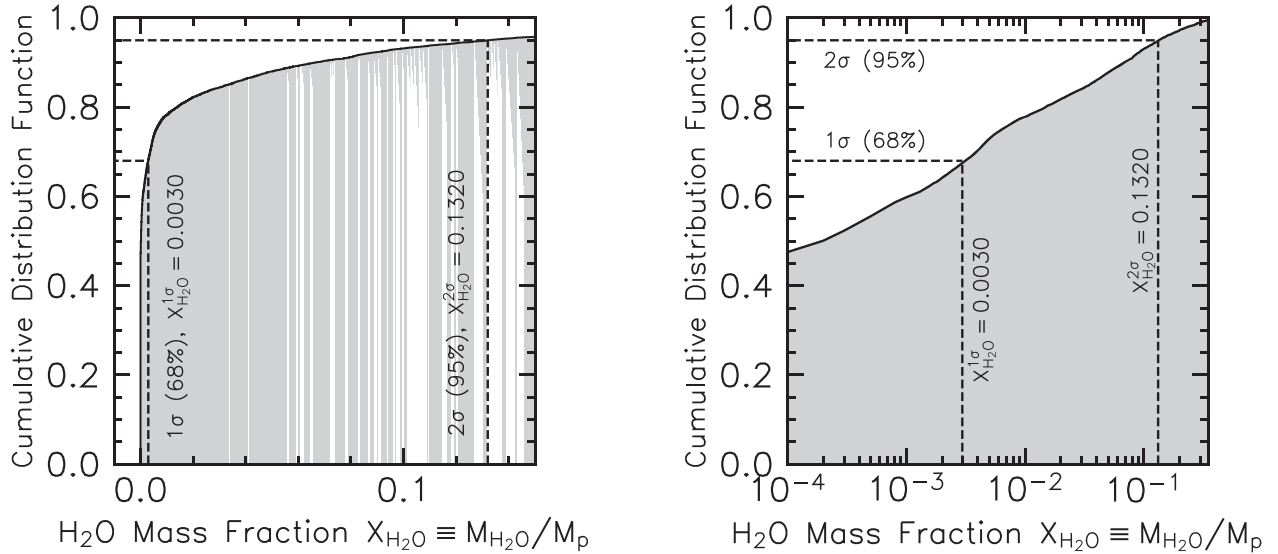


Figure 5. The distribution of water mass fractions is shown for the population of super-Earths under the scenario of no outgassing and no atmospheric stripping at an equilibrium temperature of 1000 K. 1σ and 2σ limits are also shown.

vast majority of samples are consistent with small water mass fractions of $\lesssim 1\%$. We calculate the 1σ (68th percentile) upper limit, denoted as $X_{\text{H}_2\text{O}}^{1\sigma} = 0.0030$. For completeness, we also include the 2σ (95th percentile), denoted as $X_{\text{H}_2\text{O}}^{2\sigma} = 0.1320$. We highlight that large uncertainties on planet mass and radius are likely driving the 2σ value. Hence, when quoting upper limits of water mass fraction, we choose the 1σ value.

We present a summary of water mass fraction upper limits for various scenarios with Earth-like iron mass fractions in Figure 6, as well as in Table 1.

3.3.1. Atmosphere Retained, No Outgassing

Starting with the scenario of retained atmosphere and no mantle outgassing, we find an upper limit of $\sim 0.3\%$, with a weak dependence on the equilibrium temperature. This is due

to the fact that planet atmospheres of a given mass and age are more inflated at higher equilibrium temperatures. Our upper limits on the water mass fraction are thus lower for higher equilibrium temperatures, which yield the same observed density for lower water content. For a typical total water mass fraction of $\sim 0.3\%$, the atmospheric mass fraction can be as low as $\sim 10^{-6}$, or equivalently ~ 0.1 bar at its base. Recall from Section 2.2 that water has a large Rosseland mean opacity, meaning that only a small atmospheric mass is required to increase a planet's transit radius significantly. This effect is more noticeable for smaller planet masses (see Figure 2).

3.3.2. Atmosphere Retained, Mantle Outgassed

Now, with the inclusion of mantle outgassing in this scenario, we see that our upper limits are reduced further to

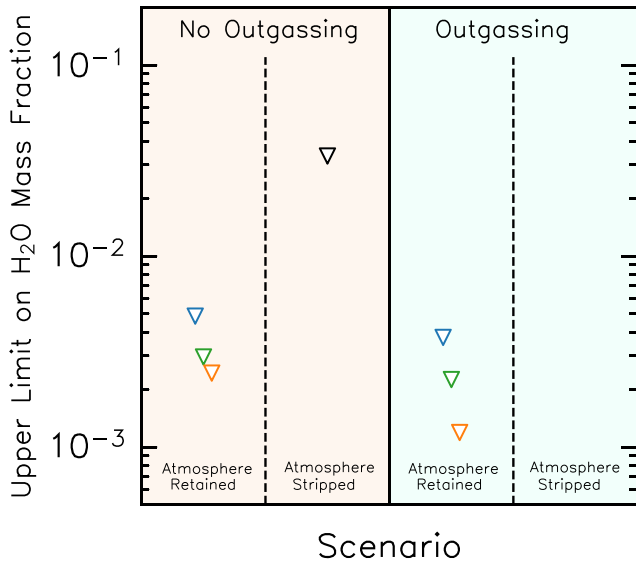


Figure 6. Summary of population-level water mass fraction 1σ upper limits for the observed sample of super-Earths. Scenarios are laid out as follows (from left to right): no outgassing and no atmospheric stripping; no outgassing with atmospheric stripping; outgassing without atmospheric stripping; and finally outgassing and atmospheric stripping. For scenarios that exhibit a dependence on the assumed equilibrium temperature of the sample, constraints at 700 K, 1000 K, and 1500 K are shown in blue, green, and orange, respectively.

Table 1

Upper Limits (1σ) on the Water Mass Fraction for Observed Super-Earths

	T_{eq} (K)	No Outgassing	Complete Outgassing
Atmosphere Retained	700	<0.0048	<0.0037
	1000	<0.0030	<0.0023
	1500	<0.0024	<0.0012
Atmosphere Stripped	...	<0.0333	...

Note. We consider various scenarios for planets with Earth-like iron mass fractions with or without undergoing atmospheric escape or mantle outgassing. We also consider models at various equilibrium temperatures of 700 K, 1000 K, and 1500 K. Note that the constraints are independent of the equilibrium temperature if the planet's atmosphere has been stripped. No constraints can be placed in the scenario of complete mantle outgassing and complete atmospheric stripping.

$\lesssim 0.2\%$. This is because releasing the water content of a planet's mantle into its atmosphere increases its size. As a result, an even lower water mass fraction is required to match the observed densities of super-Earths. As with the previous scenario, the same dependence with equilibrium temperature exists.

3.3.3. Atmosphere Stripped, No Outgassing

The scenario of atmospheric stripping without mantle outgassing provides an upper limit on water mass fraction of $\lesssim 3\%$. This scenario is the most stringent since there is no remaining atmosphere to inflate the planet. Instead, a planet's density is controlled by varying the water content locked inside its mantle and iron core. Since the compressibility of a gas is far greater than that of silicate/iron, more water is required to achieve the same reduced density. Note that the water mass fractions for scenarios with atmospheric stripping are

independent of the equilibrium temperature since there is no atmosphere to inflate/contract as a function of incident flux.

3.3.4. Atmosphere Stripped, Mantle Outgassed

Our final scenario, which comprises total mantle outgassing and total atmospheric stripping, yields no constraints. This is because, from an initial maximum water mass fraction in our scenario grids of $X_{\text{H}_2\text{O}} \sim 0.4$, outgassing and stripping lead to the water content being reduced to $X_{\text{H}_2\text{O}} \lesssim 0.05$, which is completely stored in the planet's iron core. As mentioned previously, the relative lack of compressibility in the iron core means that water mass fractions of $\gtrsim 0.4$ (before stripping) are required to fit the observed densities of super-Earths. Since our models are unable to reach such values in a reliable manner, we cannot place limits on this scenario.

3.4. Mass-dependent Limits of Water Mass Fraction

We now split our sample of super-Earths into three bins in planet mass and find the upper limits of water mass fraction for each bin. We choose bin edges of $M_p = [0.5, 2.5, 5.5, 10.0] M_{\oplus}$, such that an approximately equal number of super-Earths sit within each bin. We present results in Figure 7, with bins shaded in different colors for clarity. The right- and left-hand panels show scenarios with and without outgassing, respectively.

We see the same trends as in Figure 6, with scenarios involving atmospheric stripping providing systematically larger upper limits. Broadly speaking, we see that planets $\lesssim 5.5 M_{\oplus}$ have larger upper limits on water content than those of larger masses, especially under the scenario of atmospheric stripping without outgassing. As discussed, a greater dynamic range in the water mass fraction is needed to account for the varying planet density under this scenario, since there is no atmosphere to inflate the planet. When considering the entire population, the constraint under this scenario is $X_{\text{H}_2\text{O}} \lesssim 0.2\%$, however, when divided into mass bins, we find an upper limit of $\sim 5\%$ in the lowest-mass bin, approximately $25\times$ higher than in the highest-mass bin.

4. Discussion

Across our various end-member scenarios for super-Earths, including processes such as atmospheric escape and outgassing, we generally find upper limits on water mass fractions of $\lesssim 3\%$, as shown in Figure 6. We now discuss the implications of these findings on their formation and evolution.

4.1. Distinguishing between Scenarios

Although end-member scenarios are informative, the true upper limit on the water mass fraction cannot be known without an understanding of which of our scenarios best describes reality.

Perhaps the best way to distinguish between scenarios with and without atmospheric stripping is with transit and emission spectroscopic observations. The upcoming 500 hr of Cycle 3 Director Discretionary Time with JWST (S. Redfield et al. 2024) aims to determine if rocky planets around M dwarfs host atmospheres. If atmospheres are indeed detected around planets close to their stars, then it implies that the mass loss of primary or secondary atmospheres is not completely efficient, perhaps due to efficient line cooling of molecular gas species, inefficient

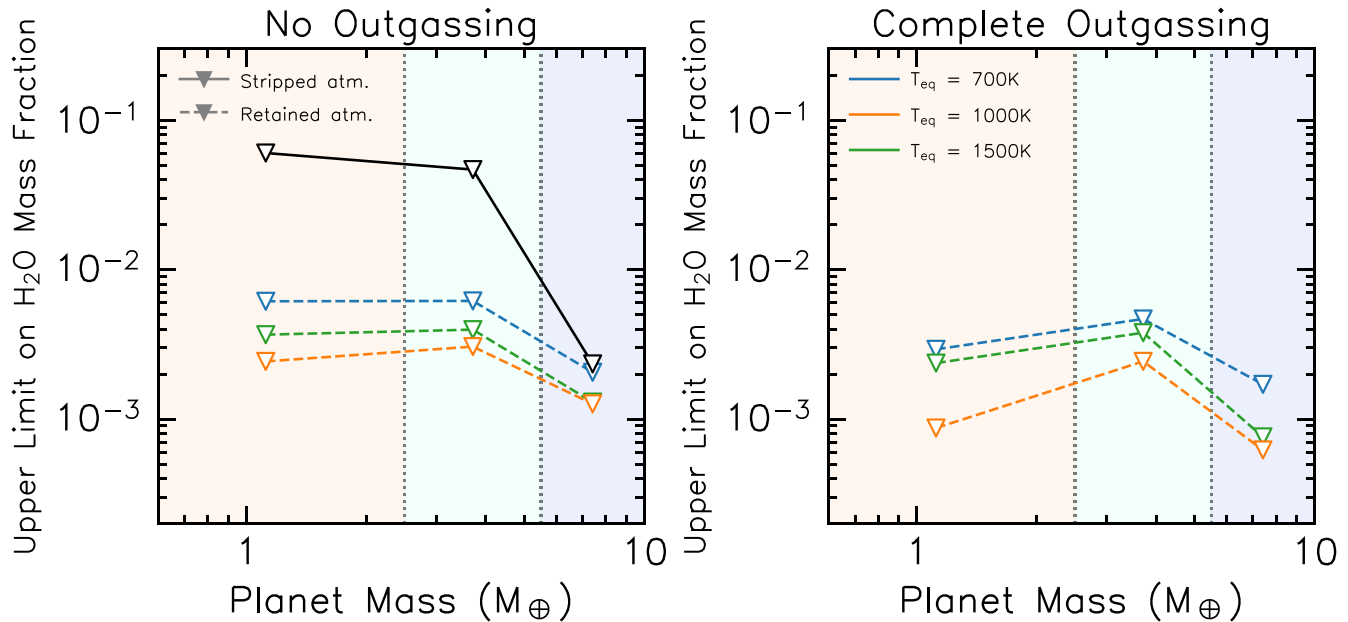


Figure 7. Water mass fraction upper limits are shown as a function of planet mass. Shaded regions represent the bin widths in planet mass, with edges at $M_p = [0.5, 2.5, 5.5, 10.0] M_\oplus$. Scenarios with and without mantle outgassing are shown in the right- and left-hand panels, respectively. Scenarios without atmospheric stripping exhibit a dependence on the assumed equilibrium temperature, which we show for 700 K, 1000 K, and 1500 K in blue, green, and orange, respectively.

drag from lighter species, or outflows becoming noncollisional. If, on the other hand, evidence is found for a lack of atmospheres,⁵ then it implies efficient escape and that more water is perhaps stored inside super-Earths, as shown in Figures 6 and 7. Although we have only focused on steam atmospheres in this study, we highlight that it is the mean molecular weights and opacities that largely control the extent of evolved atmospheres (see Figures 1 and 2). Inference of other high mean molecular weight species (e.g., CO, CO₂, CH₄, and NH₃) will also provide crucial information that can be used to inform super-Earth water budgets in future studies.

Mantle outgassing is arguably the more difficult scenario to place constraints on since it is poorly understood beyond the context of solar system bodies and depends on many factors, such as the degree of magma ocean crystallization and the presence of a crust (e.g., J. A. Crisp 1984; C. Dorn et al. 2018b; F. Gaillard et al. 2021; C. M. Guimond et al. 2021; J. Krissansen-Totton & J. J. Fortney 2022). Typically, outgassing is investigated in the context of Earth-like carbon cycles; however, for super-Earths with larger water mass fractions and potentially deep ocean layers, the abundance of H₂O may change the oxidation state of the interiors, thus changing the chemical signatures of outgassing. Again, atmospheric characterization may shed light on this topic, although we highlight that more theoretical work is needed to interpret such observations.

We speculate that the most realistic end-member scenario, given our current understanding, is that of atmospheric stripping without mantle outgassing. While outgassing is likely an important process in terrestrial planet evolution, mantles are unlikely to completely outgas. Regarding atmospheric stripping, super-Earths typically exhibit extreme equilibrium temperatures and are unlikely to retain a significant, optically thick, steam-dominated atmosphere. H₂O is likely to photodissociate, allowing

hydrogen to drag oxygen along in the outflow. Of course, these scenarios are end-members, and reality will likely be a mixture of processes, e.g., partial outgassing and near-complete stripping. Nevertheless, the combination of our scenario results suggests upper limits of order $\sim 1\%$. In order for a larger water mass fraction to have been present (such as those in proposed sub-Neptune “water worlds” with typical fractions of $\gtrsim 50\%$; e.g., L. Zeng et al. 2019; R. Luque & E. Pallé 2022; R. Burn et al. 2024), one would need near-total outgassing of mantle water and total atmospheric stripping. We encourage further studies to investigate the likelihood of such a scenario.

4.2. On the Origins of Water

Throughout this study, we have been agnostic as to the origin of water on super-Earths. One mechanism capable of providing an abundance of water is via delivery through pebble or planetesimal accretion (e.g., R. Machida & Y. Abe 2010; T. Sato et al. 2016; S. Ida et al. 2019; M.-L. Steinmeyer et al. 2023). However, another route to water is through its production as a result of chemical reactions. In J. G. Rogers et al. (2024b), super-Earths were modeled under the assumption that they began life as sub-Neptunes, with primordial hydrogen-rich atmospheres accreted from their nascent protoplanetary disks. Using the models of H. E. Schlichting & E. D. Young (2022) and E. D. Young et al. (2023), the authors solved for global chemical equilibrium on super-Earths, accounting for the loss of hydrogen as it was removed via thermally driven atmospheric escape. They found that a large fraction of water can be produced as a result of hydrogen chemically reacting with a magma ocean, which is then primarily stored in the planet’s iron core as atomic H and O. Figure 8 compares these models, which were performed for super-Earths at equilibrium temperatures of 1000 K, with our upper limits under the scenarios of no outgassing at the same equilibrium temperature. In general, we see good agreement with the models of J. G. Rogers et al. (2024b), particularly in the case of atmospheres being stripped. This suggests that the

⁵ A corollary of this finding would be that mass-loss timescales are shorter than outgassing timescales.

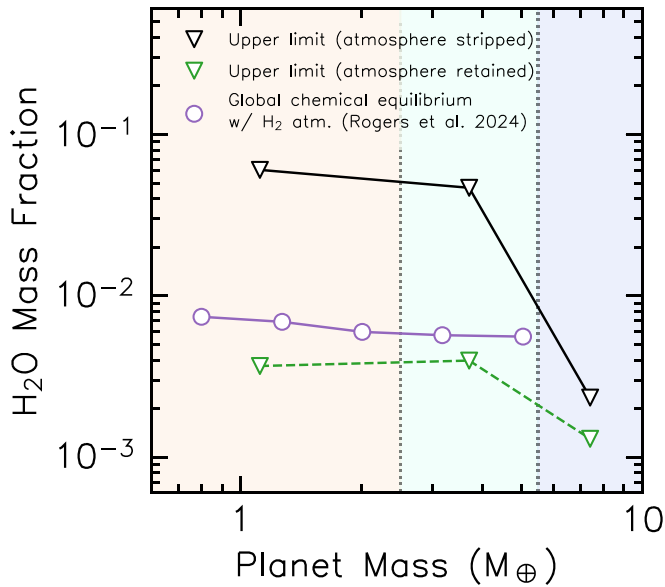


Figure 8. Similar to the left-hand panel of Figure 7, but compared to the models of J. G. Rogers et al. (2024b). These models determine the water mass fraction produced as a result of the chemical equilibration of primordial hydrogen-dominated atmospheres with magma oceans.

water content of most super-Earths can be explained as the result of chemical equilibration with a primordial hydrogen-dominated atmosphere. This is similar to the argument of E. D. Young et al. (2023), who argued that Earth's water content could be explained as a result of a primordial hydrogen-dominated atmosphere equilibrating with a magma ocean (see also J. Wu et al. 2018). In the sub-Neptune regime, B. Benneke et al. (2024) showed that the mean molecular weight of TOI-270 b's atmosphere, as observed by JWST, can be explained by the production of H_2O (among other volatile species) via equilibration of its hydrogen-dominated atmosphere with a magma ocean.

Placing super-Earths in the context of all known small planets, including Earth, and combining with the observational evidence in favor of hydrogen-dominated atmospheres on small exoplanets (e.g., D. Jontof-Hutter et al. 2014; L. A. Dos Santos 2023) potentially leads to a concise story for the origin of water via chemical reactions with a magma ocean. This is backed up by numerous experimental studies, highlighting the efficient production of water when hydrogen reacts with silicate magma (e.g., A. Shinozaki et al. 2014; T. Kim et al. 2023; H. Horn et al. 2023; H. W. Horn et al. 2023).

4.3. Benchmarking the Models

In Section 4.2, we compared our models with those of J. G. Rogers et al. (2024b). Here, we highlight that there are notable distinctions in the interior models adopted in this work from H. Luo et al. (2024; see Section 2.1) from those of J. G. Rogers et al. (2024b). The latter solves a complex network of chemical equilibria throughout the planet; however, it is limited in the complexity regarding interior structure (e.g., pressure and temperature profiles). The models of H. Luo et al. (2024), on the other hand, solve for pressure and temperature profiles but only track water as a chemical component. Furthermore, both models adopt different H_2O solubility law scalings, with those of H. Luo et al. (2024) assuming H_2O

dissolves in a magma ocean as OH^- , as suggested by experiments at low pressure (e.g., D. L. Hamilton et al. 1964). H. E. Schlichting & E. D. Young (2022) and J. G. Rogers et al. (2024b), on the other hand, assumed ideal mixing of H_2O in a magma ocean due to the lack of evidence for the former being true at high pressures. Finally, H. Luo et al. (2024) assumed partitioning coefficients of H_2O between the mantle and iron core that assume water remains in its molecular form, whereas H. E. Schlichting & E. D. Young (2022) and J. G. Rogers et al. (2024b) assume H_2O speciates into atomic H and O due to the extreme temperatures and pressures.

Due to these differences, we performed a simple comparison to confirm that both interior models yield similar inferences of the total water mass fraction for the observed population of super-Earths. With the goal of consistency, we adapted the models of H. E. Schlichting & E. D. Young (2022) and J. G. Rogers et al. (2024b) to allow for water dissolving in silicate melt as OH as in C. Dorn et al. (2018a) and H. Luo et al. (2024). We then produced a small grid of planet models of varying water mass fraction at $4 M_\oplus$ at an equilibrium temperature of 1000 K and evolve their steam-dominated atmospheres with the method described in Section 2.2. We then repeated the water mass fraction upper limit calculation (as described in Section 3.2) for a small sample of observed super-Earths with $3 \leq M_p/M_\oplus < 5$. We found that the upper limit with the interior models of J. G. Rogers et al. (2024b) is $\sim 0.9\%$, compared to 0.5% for models constructed in this work. This small difference is reassuring, given the differences in formalism between the models of J. G. Rogers et al. (2024b) and H. Luo et al. (2024).

4.4. Assumptions and Limitations

The results of this study have relied upon interior models of rocky super-Earths. These models are built upon experimentally or computationally derived partitioning coefficients, solubility scalings, and equations of state. It is clear that more work is needed to refine and validate our understanding of volatile sequestration in rocky planets. Furthermore, our models have been limited to a single volatile species, namely H_2O . In reality, the chemistry involved is far more complex, with other oxygen-, carbon-, nitrogen-, and sulfur-bearing species likely present in atmospheres and interiors. Studying their behaviors in atmospheres, as well as under high pressures and temperatures, is crucial in order to move beyond simple models.

An important simplifying assumption of this work has been to assume Earth-like iron mass fractions for super-Earths. While this iron-to-silicate ratio is supported by various lines of evidence, as discussed in Sections 1 and 2.3, it is worth noting that changing the iron mass fraction of a planet also changes its bulk density. Adopting the same approach as with our other scenarios, we consider the end-members of this change. We performed our statistical analysis again under the assumption that super-Earths have Mercury-like iron mass fractions of 69%. The increased iron mass fraction increases the density of a planet's interior for a given mass. Thus, larger water mass fractions are required to match observed super-Earth densities. In the case of no atmospheric stripping and no outgassing, we find $X_{\text{H}_2\text{O}}^{1\sigma} < 0.1723, 0.1477, \text{ and } 0.1168$ for equilibrium temperatures of 700 K, 1000 K, and 1500 K, respectively. In the case of no stripping and complete mantle outgassing, we

find $X_{\text{H}_2\text{O}}^{1\sigma} < 0.0813$, 0.0569, and 0.0353 for equilibrium temperatures of 700 K, 1000 K, and 1500 K, respectively. As expected, these are larger than those of Earth-like iron mass fractions (see Table 1), although the physical validity of this scenario is somewhat unlikely, since it would likely require mantle stripping via dynamically induced collisions (e.g., W. Benz et al. 1988), which would then remove any atmosphere. There is also a lack of evidence for the existence of super-Mercuries in polluted white dwarf data (A. E. Doyle et al. 2020). We were unable to find reasonable constraints on water mass fractions in the case of atmospheric stripping since an extremely large water mass fraction is required to match the densities of observed super-Earths. The opposite end-member scenario consists of planets without iron cores. We find that this scenario is inconsistent with the vast majority of super-Earths, which are denser than a pure (dry) silicate composition and thus require a water mass fraction of $X_{\text{H}_2\text{O}} = 0$. The population-level upper limits would thus be very small $X_{\text{H}_2\text{O}}^{1\sigma} < 10^{-4}$ and uninformative.

Finally, our inferred water mass fraction limits have also relied up on the precise characterization of observed super-Earths. We highlight, however, that this sample is inherently biased since radial velocity programs preferentially target stars with larger signals. Our constraints are, therefore, indicative of the observed population and not the underlying population. We encourage future studies to address survey bias to quantify this effect. In addition, increasing the precision of mass measurements, and increasing the available sample size with missions such as TESS (G. R. Ricker et al. 2015) and PLATO (H. Rauer et al. 2014) will refine our inferences in future studies.

5. Conclusions

In this work, we have focused on the water content of super-Earths. We combine the interior models of H. Luo et al. (2024) with atmospheric evolution models to construct grids under various end-member evolutionary outcomes, including efficient mantle outgassing and/or atmospheric escape. These mass–radius relations are made publicly available at doi:10.5281/zenodo.14172976. By comparing these models with an observed sample of super-Earths from the PlanetS catalog (J. F. Otegi et al. 2020; L. Parc et al. 2024), we place upper limits on the water mass fractions of super-Earths at the population level. Our conclusions are as follows.

1. In the scenario that super-Earths retain a thin steam atmosphere, we find a 1σ upper limit on the water mass fraction of $\sim 0.3\%$, with a weak dependence on the assumed equilibrium temperature.
2. In the scenario that super-Earths do not host atmospheres, possibly due to thermally driven escape, this water mass fraction upper limit increases to $\sim 3\%$.
3. In the scenario that super-Earths outgas the entire water content of their mantles into a steam atmosphere, the upper limit reduces further to $\sim 0.2\%$. If this outgassed steam atmosphere is stripped, then we are unable to place any constraint on the original water mass fraction.
4. Larger super-Earths of $\gtrsim 5 M_{\oplus}$ tend to have systematically lower water mass fractions than those with lower masses.

Our study is designed to consider end-member scenarios, with reality likely sitting somewhere in between, e.g., partial outgassing and significant atmospheric escape. Nevertheless, our combined water mass fraction upper limits are consistent

with studies suggesting that reactions between primordial hydrogen-dominated atmospheres and magma oceans can produce $\sim 1\%$ water (J. G. Rogers et al. 2024b). Similar arguments have been proposed for Earth's water budget (E. D. Young et al. 2023), suggesting that the water content of small planets may be produced, instead of delivered.

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