THE SMALL EXOPLANET EVOLUTION SEQUENCE: FROM SUB-NETUNES TO SUPER-EARTHS.

Edwin S. Kite\textsuperscript{1}, Megan Barnett\textsuperscript{1}, Bruce Fegley\textsuperscript{2}, Laura Schaefer\textsuperscript{3}, Eric B. Ford\textsuperscript{4}. 1. University of Chicago, Chicago, IL (kite@uchicago.edu), 2. Washington University, St Louis, MO. 3. Stanford University, Stanford, CA. 4. Pennsylvania State University, University Park, PA.

Fig. 1. Cartoon of the small exoplanet evolution sequence. 

Summary: The two most common types of known exoplanet are the sub-Neptunes (planet radius $R = 2$ - $3 \, \text{R}_\oplus$, planet density $\rho \lesssim 3 \, \text{g/cc}$) and the rocky super-Earths ($R < 1.6 \, \text{R}_\oplus, \rho > 4 \, \text{g/cc}$) (e.g. [1]). Strong indirect evidence implies that sub-Neptunes have massive magma oceans blanketed by thick hydrogen-dominated atmospheres (e.g., [2]). A substantial fraction of planets that are born with $>10 \, \text{kbar H}_2$-dominated primary atmospheres lose those atmospheres and shrink in radius to become super-Earths [3]. It is plausible that most of the known rocky exoplanets were born as sub-Neptunes, but sub-Neptunes have no solar system analog. Therefore, we used models to study sub-Neptunes’ size, chemistry, and legacy. We focus on the interaction between the magma ocean and the hydrogen-dominated atmosphere. Results include:

1. Dissolution of the atmosphere into the magma explains the drop-off in exoplanet abundance at $3 \, \text{R}_\oplus$ [4]. This radius cliff is the major feature in the exoplanet radius distribution (Fig. 2).

2. If magma and atmosphere equilibrate, then magma-atmosphere interactions are key to sub-Neptune atmosphere chemistry, and may contribute to the paucity of exoplanets with $R = 1.5$ - $2 \, \text{R}_\oplus$ (Fig. 3).

3. Transition from a sub-Neptune to a super-Earth with a high mean-molecular-weight atmosphere (high-$\mu_{\text{atm}}$) exsolved from the magma ocean is unlikely (considering initial CO$_2$ and H$_2$O contents similar to that of present-day Earth) (Fig. 4).

Why are sub-Neptunes common but Neptune-sized exoplanets rare? We propose that the drop-off in exoplanet abundance at $3 \, \text{R}_\oplus$ is so abrupt because at $R \sim 3 \, \text{R}_\oplus$ base-of-atmosphere pressure is high enough for the atmosphere to readily dissolve into magma, and this sequestration acts as a strong brake on further growth [4]. As the base-of-atmosphere pressure nears $10 \, \text{GPa} \sim (3 \, \text{R}_\oplus)$, more and more of the H$_2$ goes into the magma (due to non-ideal fugacity effects), so the radius does not increase much (Fig. 2).

What sets the chemistry of sub-Neptune atmospheres? That H$_2$ dissolution in magma can explain the radius cliff suggests magma-atmosphere equilibration on sub-Neptunes. We studied Fe + H$_2 \leftrightarrow FeO + H_2O$ reaction (e.g. [5]) in the context of the sub-Neptune magma-atmosphere interface (Fig. 3). Assuming magma-atmosphere equilibration, we find: (i) Most volatiles are stored in the magma. (ii) Turning a sub-Neptune into a Super-Earth requires more H loss than is usually assumed. The extra demand on H loss may stress-test H loss models. (iii) For low volatile doses, much of the H$_2$ is converted to H$_2$O, which is readily soluble in the magma – a redox-enabled solubility pump. (iv) Combining these effects, a smooth distribution of gas supplied from the nebula yields a bimodal planet radius histogram. The first mode has $\mu_{\text{atm}} = 2$ and atmospheres $\sim 10^4 \, \text{km}$ thick. The second mode corresponds to worlds with most volatiles stored as dissolved “$\text{H}_2\text{O}$”, atmospheres $\sim 10^3 \, \text{km}$ thick, and $\mu_{\text{atm}} = 3 - 7 \, \text{Da}$. These cryptic sub-Neptunes are separated from classic sub-Neptunes by a radius valley (which is made deeper by atmospheric loss). Cryptic sub-Neptunes may be distinguishable from super-Earths with TESS + TFOP data. The extent of magma-atmosphere equilibration depends on the timing of core assembly vs. atmosphere accretion, plus the characteristic size of impacts. Equilibration need not be complete, because a little bit of magma goes a long way.

The small planet evolution sequence explains the conditions under which rocky worlds that initially have thick primary atmospheres can evolve into super-Earths with secondary atmospheres. Can super-Earths have secondary atmospheres Gyr after primary-atmosphere loss? When the atmosphere contains both H$_2$ and a soluble high-$\mu$ constituent, H$_2$ is less protected by sequestration within the magma, so H$_2$ takes the brunt of atmosphere loss processes that might otherwise remove the high-$\mu$ species. On the other hand, the escaping H$_2$ can entrain high-$\mu$ species. To track these (and other) competing processes, we modeled the small planet evolu-
Our key assumption is that the high-\(\mu\) volatiles are delivered in a mass fraction similar to the present-day H+C mass fraction of bulk silicate Earth, at a time when the H\(_2\) atmosphere is \(\sim\)50 kbar.

Fig. 2. Histograms of planet abundance. Colored bands are the true planet histogram (with error) according to \([6]\) (light gray) and according to \([7]\) (dark gray). Lines show model output for the impermeable planet case (black line); linear (Henry’s Law) dissolution of H\(_2\) in magma (blue line); and the fugacity crisis case (red line). Triangles correspond to the bare-core radii for \(\{4,6\}\) M\(_{\oplus}\). See \([4]\) for details.

Neglecting diffusive separation within the atmosphere (which we justify a posteriori) the output is time-independent. Thus we calculate time-independent small exoplanet evolution sequences (quantitative versions of Fig. 1) and then map them on to the time-dependent specifics of atmosphere loss for a given planet’s environment. To make the curves shown in Fig. 4, we adopt an energy-limited escape flux at \(\mu = 2.3\) with the \(L_{\text{XUV}}/L_{\text{bol}}\) of \([8]\), XUV heating efficiency \(\varepsilon = 0.15\), and the planet radii of \([9]\); transitioning to the pure-CO\(_2\) escape flux of \([10]\) at high \(\mu\).

We find that, for most worlds that are born as sub-Neptunes, exsolution of high-\(\mu\) constituents from the magma ocean is usually not enough to overcome dilution by nebular gas. As a result, the atmosphere stays H-dominated and the high-\(\mu\) constituents are entrained to space. Exceptions occur (e.g., Fig. 4). For super-Earths that are born as sub-Neptunes, volcanic outgassing driven by solid-state mantle convection should continue for Gyr (e.g., \([11]\)). However, silicates are depleted in volatiles during the sub-Neptune to super-Earth conversion process. Overall, for currently known Super-Earths, which typically orbit Solar-mass stars, volcanic atmospheres are plausible at high insolations. For planets around \(\sim\)0.3 M\(_{\odot}\) stars, secondary atmospheres at \(>4\) L\(_{\oplus}\) are unlikely unless the planet includes a major contribution of solids from beyond the H\(_2\)O ice line (waterworld).

Fig. 3. Adding H\(_2\) to a magma ocean of 3.3 M\(_{\oplus}\) with a temperature at the magma-atmosphere interface of 3000 K. Simplified Fe-Mg-Si-O-H model. For H\(_2\)-free magma oxidation state near the upper end of the range found from white dwarf analysis \([12]\).

Fig. 4. Planet evolution tracks, varying distance from 1 M\(_{\odot}\) star. Exsolution of highly-soluble-in-magma secondary-atmosphere constituent leads to high \(\mu_{\text{atm}}\) (color change) as atmosphere shrinks. However, in most cases, the XUV flux is so high at this point that the high-\(\mu_{\text{atm}}\) atmosphere is short-lived. Fine-tuning is needed to produce a long-lived high-\(\mu_{\text{atm}}\) state (rightmost tracks). Planets far from star stay as sub-Neptunes (uppermost track).

Acknowledgements: G. Gilbert, D. Fabrycky. Funding: Primary: NASA (NNX16AB44G). Additional support: NASA (NNX17AC02G), NSF (AST-1517541), and the Penn State Center for Exoplanets and Habitable Worlds.