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Origin of the Atmospheres of Exoplanet Sub-Neptunes and Super-Earths

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1. Introduction.

Using exoplanet atmosphere mass/composition to constrain planet formation and evolution is a core goal of exoplanet research [1]. R < 4 Earth-radii (R_E) exoplanets are found in two modes: R = 2.4±0.5 R_E worlds with densities < 4 g/cc (sub-Neptunes), and R = 1.4±0.4 R_E worlds with bulk density indicating Earth-like composition [2]. Sub-Neptunes probably have 10^3-10^4-km-deep H_2-rich atmospheres cloaking rocky cores. Thus, they are mostly atmosphere by volume, and mostly silicate by mass (e.g. [3-5]). Super-Earths may be genetically related to sub-Neptunes by H_2 removal. Whether or not they have atmospheres is unknown. For both classes of worlds, the silicate core dominates the mass, and so we might expect core-atmosphere reactions would set atmosphere mass, volatile speciation (redox) and volatile partitioning (atmosphere, versus dissolved in the silicate) [6-8]. Perhaps surprisingly, no previous study has investigated either of the following:

- How does magma-atmosphere equilibration set atmosphere composition for sub-Neptunes?
- How do magma oceans affect the presence/absence of outgassed atmospheres on rocky exoplanets?

2. Origin of sub-Neptune atmospheres.

To explore atmosphere-magma reactions, we first consider a silicate magma that is redox-buffered by coexistence of Fe and "FeO":

$$(1\text{-}x)\mathrm{Fe} + \tfrac{1}{2}\,\mathrm{O_2} = \mathrm{Fe_{1-x}O} \qquad (1)$$

i.e. an Fe-"FeO" buffer. With x ~= 0.05, this can be thought of as the iron-wüstite / IW buffer; however we apply the buffer to temperatures above the wüstite melting point. To fix ideas, we neglect all elements except for Fe, Mg, Si, O, and H, suppose that 1600 K < T < 2500 K, and suppose further that pressures at the interface are <1 kbar so that for the purposes of order-of-magnitude calculation we can treat the atmospheric gases as ideal. The oxygen fugacity fO_2 is then given by standard data [9]. fO_2 scales as the square of the activity of wüstite (e.g., [10]). This is confirmed by the output of our Gibbs free energy minimization code, IVTAN, for the Fe-Mg-Si-O-H system. The H_2/H_2O ratio in the atmosphere is set by fO_2 [9], via $H_2 + \frac{1}{2} O_2 = H_2O$. Thus, the net reaction is $FeO + H_2 = Fe + H_2O$. The H_2 solubility at the top of the magma layer is approximated following [11], and the H_2O solubility at the top of the magma layer is approximated by [12]. We then find mass balance for H between the four reservoirs. The main result is that even for IW-2 or IW-4, it is very easy for most H to be stored in the magma as H_2O, even when the atmosphere is mostly H_2, and even when H is derived from the nebula and not from outgassing. This is because H_2O is much more soluble in silicate magma than is H_2. (This is in addition to the previously noted [6] effect of H dissolution into the magma). As a result, the fate of H in mini-Neptunes is to cycle between the atmosphere and the magma. Thus the fraction of H in the atmosphere can be small, and this holds more strongly if H dissolves in an Fe-metal core. Oxidation states similar to that of carbonaceous chondrites, ordinary chondrites, or achondrites predict higher mantle FeO than for enstatite chondrite composition. Buffers like (1) can be overwhelmed if so much H is added from the nebula that *all* Fe is reduced to Fe^0. The amount of H needed for this will be controlled by the oxidation state of the embryos (±pebbles) that collide to form the rock+metal cores, as reflected by silicate FeO content. We do not know how magma-cores grow, nor where the growth happened (formation in-situ, migration from

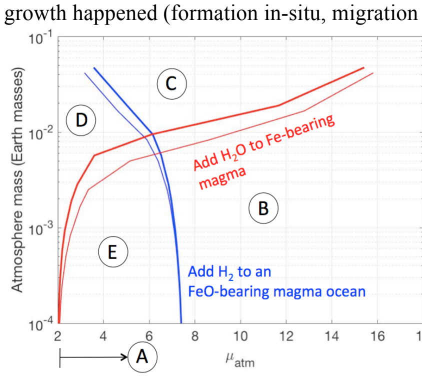

Fig. 1: Trade-off between atmosphere mass and atmosphere molecular weight (at atmosphere-magma interface T = 2500K). Thin line: 1 M_E, thick line: 5 M_E. See text for **(A)-(E)**.

<1 AU, or migration from beyond the ice-line?), nor where the volatiles came from (outgassing, or nebular accretion?) [e.g., 13-14]. These hypotheses make distinct predictions for magma redox, summarized in Fig. 1. Atmosphere mean molecular mass (μ_{atm}) and atmosphere mass (X_{atm}) are potentially a probe of planet formation processes (letters refer to Fig. 1):

(**A**) High H_2O/H_2 ratio → planetesimal-or-planet migration (pebble migration or in-situ formation ruled out). The simplest explanation for a high H_2O/H_2 ratio (oxidation) is interaction with molten water followed by H_2 loss (size >1 km; [15]). High H_2O/H_2 in the atmosphere excludes pebble migration.

(**B**) $\mu_{atm} > 7 \rightarrow$ planet migration. Sub-Neptune atmospheres cannot reach μ_{atm} >7 by reactions between magma and nebula gas. Therefore, atmospheres with μ_{atm} >7 imply outgassing of volatile H_2O and C-species. Because the icelines for these species are at $p > 10^2$ days, $\mu_{atm} > 7$ implies migration of embryos or planets.

(**C**) Water-buffered worlds. The area that is above both the red and blue lines in Fig. 1 (top panel) with $\mu_{atm} > 3$ has a μ_{atm} and atmospheric mass that requires bulk delivery (and retention in an envelope) of volatiles, and cannot be explained by gas release by reaction of nebula material with the silicate core. These worlds likely gathered a major contribution from H_2O.

(**D**) $\mu_{atm} < 7$, plus $(X_{atm}M_{pl}) > 0.01\ M_\oplus \rightarrow$ nebula accretion. Points above the red line cannot be accessed by outgassing (i.e., gas release by magma-atmosphere reactions). Embryo-embryo collisions shred protoatmospheres (e.g. [16]), so such worlds probably reached near-full mass in the presence of the nebula.

(**E**) Zone of overlap = ambiguous origins.

3. Presence/absence of atmospheres on warm Super-Earths: magma (probably) matters.

We are currently investigating mechanisms linking magma ocean evolution to the presence/absence of atmospheres on warm (T_{eff} = 400 – 1200K) Super-Earths [17]. Results will be reported at the conference.

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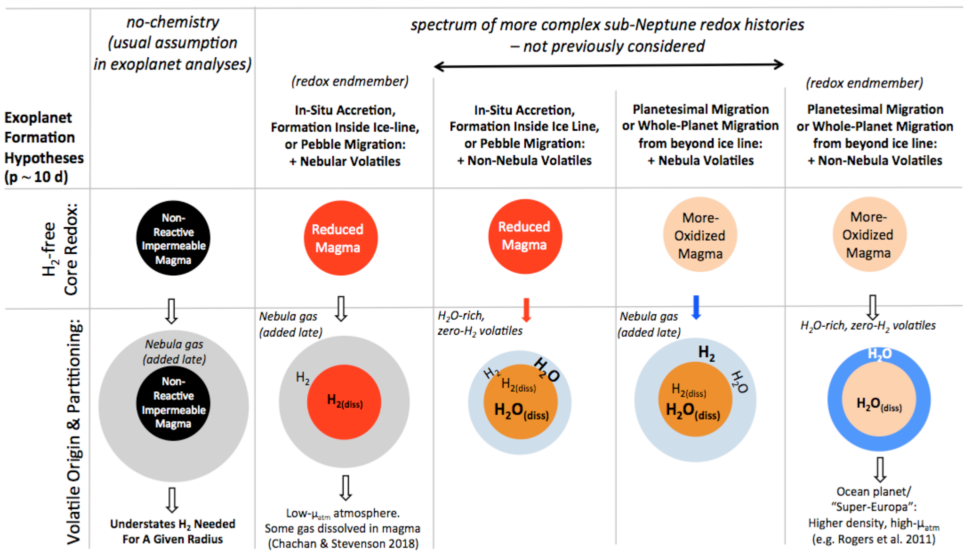

Fig. 2. Cartoon summary of sub-Neptune redox histories and the consequences for atmosphere mass/composition.