THE IMPORTANCE OF SILICATE VAPOR IN DETERMINING THE STRUCTURE, RADII, AND ENVELOPE MASS FRACTIONS OF SUB-NEPTUNES. William Misener1 and Hilke E. Schlichting1,  
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Introduction: Planets with radii between those of Earth and Neptune are the most common type of exoplanet discovered to date [1]. Further refinements of these planets’ parameters have shown that many have bulk densities consistent with rock-dominated cores topped by H/He gas envelopes, which are typically thought to be a few percent of the planets’ total mass [2]. The atmospheric mass fractions of these planets cannot be directly measured, however. Instead, models of a planet’s interior structure and thermal evolution are needed to infer the envelope mass. Such models have assumed these ‘sub-Neptunes’ are composed of discrete layers of gas and rock [3]. But formation models predict that these planets form with high interior temperatures, exceeding 5000 K at the base of the atmosphere, where the H/He gas is in contact with the silicate-dominated interior [4]. Recent chemical equilibrium simulations at the atmosphere-interior interface of sub-Neptunes reveal that substantial silicate vapor is expected to be in the gas phase at these conditions [5]. This silicate vapor cannot be neglected in atmospheric structure calculations, as it will act as a condensable species, decreasing in abundance with altitude. The condensation of a heavy species in a lightweight background atmosphere causes a mean molecular weight gradient to develop. Such a gradient can inhibit convection if sufficient condensable gas is present, dramatically altering the atmospheric structure expected deep within these exoplanets. This physical mechanism has long been recognized in the context of Solar System planets, in which the condensable considered is usually water [6,7,8]. Similar gradients in mean molecular weight have also been suggested to arise from the accretion of rocky planetesimals and their vaporization during in-fall [9]. We extend these physical arguments to the conditions relevant in sub-Neptune interiors, in which the bottom of the H/He atmosphere interfaces with a silicate magma ocean.

Results: We show that the mean molecular weight gradient resulting from the condensation of silicate vapor in sub-Neptune atmospheres inhibits convection at temperatures above ~4000 K, inducing a near-surface radiative layer. The planetary structure we consider is illustrated schematically in Figure 1. This radiative layer is highly super-adiabatic for realistic opacity assumptions, which leads to a decrease in a planet’s overall radius compared to a model with the same base temperature and a convective, pure H/He atmosphere. Therefore, we expect silicate vapor to affect the thermal evolution and inferred envelope mass fractions of sub-Neptune planets. By constructing a planetary thermal evolution model which incorporates these novel atmospheric structures, we demonstrate that differences in radii, and hence in inferred atmospheric masses, are largest for planets which have larger masses, equilibrium temperatures, and atmospheric mass fractions. The discrepancies between our models and previous, fully convective models are largest for younger planets, but differences can persist on gigayear timescales for sub-Neptunes with larger inventories of H/He, which we depict in Figure 2. For example, for a 10 M⊕ planet with Teq = 1000 K and an age of ~300 Myr, an observed radius consistent with an atmospheric mass fraction of 10 percent when accounting for silicate vapor would be misinterpreted as indicating an atmospheric mass fraction of 2 percent if a H/He-only atmosphere were assumed [10].

Implications: The misinterpretation of atmospheric masses due to this silicate-induced deep
radiative zone implies that some sub-Neptunes could have more massive atmospheres than previously inferred. The presence of a radiative layer may affect atmospheric mass loss from young sub-Neptunes after the disk disperses, which leading mechanisms for explaining observed exoplanet demographics suggest is common [11,12]. However, the exact impact of these novel structures is not entirely clear. For example, under the core-powered mass loss mechanism, competition between the cooling of the underlying core and thermal escape determine whether a planet loses its atmosphere. We have shown that both a planet’s luminosity and its radiative-convective boundary location, which sets the mass-loss rate, are impacted by an inner radiative region. A self-consistent assessment of the impacts of an inner radiative region on mass loss will also need to consider a planet’s accretion phase, which sets both the initial atmospheric mass and the thermal state of the underlying core. The extreme temperatures and pressures expected during accretion will require consideration of super-critical silicate-hydrogen mixtures, the physical characteristics of which are not yet well understood [13].

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