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Hydrogen-silicate-iron miscibility and implications for the demographics of sub-Neptunes and super-Earths

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Sub-Neptunes and their super-Earth cousins together comprise the most abundant planet types per star in the Galaxy. Sub-Neptunes are characterized by bulk densities intermediate between those of rocky planets and Neptune-like planets. Super-Earths are thought to be mainly the result of stripping of sub-Neptune envelopes/atmospheres. These planets can be divided into four broad groupings: Lava worlds with secondary atmospheres (e.g., planet 55 Cancri e), planets transitional in bulk density between rocky super-Earths and sub-Neptunes (e.g., planet LHS 1140 b), sometimes identified as potential water worlds, higher-density sub-Neptunes that exemplify the degeneracy between water-rich rocky planets and those with significant H_2/He envelopes (e.g., planet K2-18 b), and lower-density sub-Neptunes with unequivocal H_2/He-rich envelopes above what are likely extant magma oceans (e.g., Kepler-36 c).

We have modeled these planets using the concept of various degrees of miscibility between molten silicate, molten iron metal, and hydrogen as prescribed by ab initio calculations and phase equilibria in this system. In this context, the boundary between supercritical magma oceans and overlying hydrogen-rich envelopes is the binodal separating the silicate/iron condensed phase and the atmosphere/envelope. When combined with models for atmospheric escape, planets modeled in this fashion can explain the full range of planet types outlined above. Planets with hydrogen < 1% by mass when they formed produce discrete, terrestrial-like metal cores, while planets born with more hydrogen are predicted to have interiors composed of a single phase. The ensemble of model planets reproduces the distributions of sub-Neptunes and super-Earths in both mass-radius space and radius-period space, and offers an overarching explanation for the wide variety of planet types in this mass range based solely on the accreted mass fractions of hydrogen-rich primary atmospheres and, importantly, the phase equilibria involving silicate, Fe metal, and H_2. The attached figure compares model planets with observed planets, showing the diversity and the match in their distribution in mass-radius space.

