

The origin of the exoplanet radius valley: the effects of photoevaporation and degassing on atmospheric composition

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More than 5,000 exoplanets have been discovered as of 2024. Fulton et al. (2017) calculated precise planet radii using data from the California-Kepler Survey. They found that the size distribution of short-period exoplanets is bimodal. This gap in frequency is referred to as "radius valley". Fulton et al. (2017) used the radius valley to define two major categories of planets: "super-Earths" and "sub-Neptunes", which correspond to planets below and above the radius valley, respectively. Sub-Neptunes are defined as planets with radii between approximately 2.0-4.0 Earth radii and distinguished by their lower densities and are thought to have thick H/He envelopes (0.1-10 wt%). In contrast, super-Earths are defined as planets with radii between approximately 1.0-1.5 Earth radii and thought to be rocky planets without thick hydrogen/helium (H/He) envelopes. Among several mechanisms proposed as origins of the radius valley, we focus on photoevaporation as a process of atmospheric loss to carve the valley. Photoevaporation is driven by high-energy X-ray and extreme ultraviolet (XUV) radiation from a host star. In this way, the atmosphere is gradually lost and the amount of the envelope decreases. A possible way to distinguish the origin of the radius valley is to utilize change in the atmospheric composition due to photoevaporation followed by degassing from the interior. During the early stages of planetary formation, the magma ocean retains dissolved volatile components, such as H, He, and other gases, within its molten state. As the atmosphere is lost and the magma ocean solidifies, these dissolved volatiles are released into the atmosphere. Thanks to the difference in their solubilities to the magma, the atmosphere is expected to become H-rich and He-poor as the replacement proceeds. This study aims to clarify the compositional (H/He) signature of the photoevaporation hypothesis for the origin of the radius valley.

We performed two theoretical approaches. With an analytic model, we newly incorporated the effect of dissolved gases into an analytic model (Lopez and Rice 2018) and derived the boundary between super-Earths and sub-Neptunes in the stellar irradiation-planetary size diagram with and without degassing; these two boundaries delineate where He-depleted planets can form. We also performed numerical model calculations of the atmospheric structure and its temporal evolution considering the stellar XUV luminosity evolution and planetary cooling (Kobayashi 2024), which predict observable properties for planets around the radius valley.

Results of the analytic model tell us where around the radius valley the atmospheric composition (H/He) is changed, provided that the valley formed with photoevaporation. In Figure 1, the purple and red lines represent the boundary between super-Earths and sub-Neptunes, with and without atmospheric replenishment, respectively. Planets above the purple line are considered to have primordial H/He envelopes, planets between the two lines are considered to have He-depleted, degassed secondary atmospheres, and planets below the red line are considered to have little to no atmospheres. Results of the numerical model quantify the He depletion and its escape rate for planets around the radius valley. From the numerical calculations, we predict that planets in this region, which have undergone degassing due to photoevaporation, will have lower He abundances (smaller than 10^{-1}) and lower helium escape rates (smaller than 10^{-1}) than planets with minimal degassing effects.

We clarified the compositional (H/He) signature of the photoevaporation hypothesis for the origin of the radius valley using both analytical and numerical calculations. These predictions can be tested with ongoing and future exoplanet observations including those for escaping He.

Keywords: Exoplanet, Radius Valley, Super-Earths, Sub-Neptunes, Atmospheres, Photoevaporation

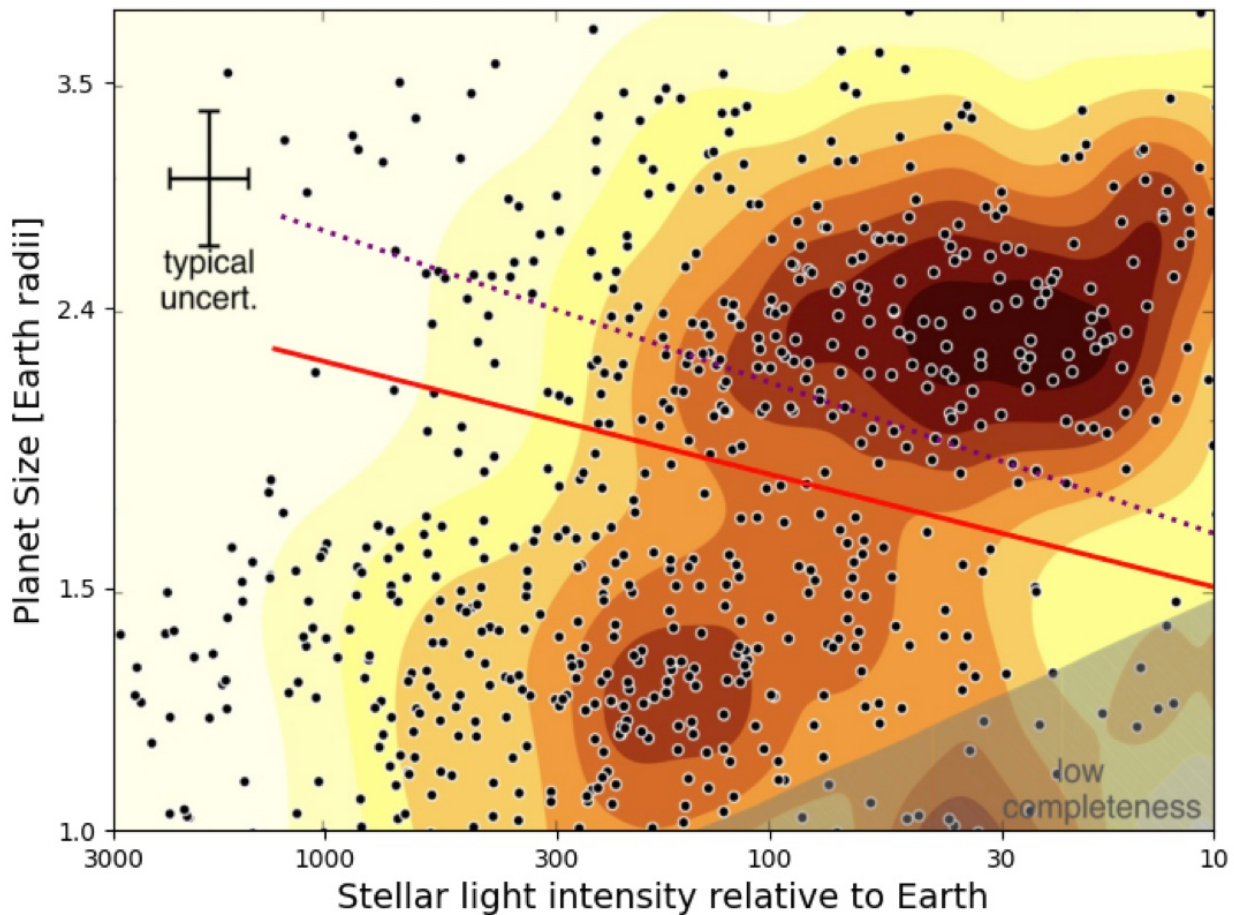


Figure 1: Thresholds for the atmospheric loss via photoevaporation obtained with our analytic model, overplotted on the exoplanet distribution of planet size and stellar light intensity. The color represents the relative occurrence of planets, with darker colors indicating higher relative occurrence. The purple and red lines represent the transition radii between super-Earths and sub-Neptunes with and without atmospheric replenishment, respectively. The exoplanet distribution is taken from the figure of Fulton et al. (2017). The median uncertainty is plotted in the upper left and the shaded region in the lower right indicates low completeness.