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Two Terrestrial Planet Families With Different Origins

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ABSTRACT

The important role of stellar irradiation in envelope removal for planets with diameters of $\lessapprox 2$ R$_\oplus$ has been inferred both through theoretical work and the observed bimodal distribution of small planet occurrence as a function of radius. We examined the trends for small planets in the three-dimensional radius-insolation-density space and find that the terrestrial planets divide into two distinct families, one of which merges with terrestrial planets and small bodies in the solar system and is thus Earth-like. The other terrestrial planet family forms a bulk-density continuum with the sub-Neptunes, and is thus likely to be composed of remnant cores produced by photoevaporation. Based on the density-radius relationships, we suggest that both terrestrial families show evidence of density enhancement through collisions. Our findings highlight the important role that both photoevaporation and collisions have in determining the density of small planets.

1. INTRODUCTION

One of the important questions in the study of exoplanets (Sotin et al. 2013) is "Are terrestrial exoplanets Earth-like, Venus-like, or the remnants of gas- or ice-giants?" Given sufficient atmospheric heating, a condition that is met for many close-orbiting planets, theoretical studies Owen & Wu (2013); Lopez & Fortney (2013, 2014); Rogers (2015) predicted photoevaporation of sub-Neptune H/He envelopes could create rocky super-Earth planets. With the original sub-Neptune envelope largely or completely removed through photoevaporation, the planet radius in this scenario is determined by the size of a rocky, or possibly icy, core. Recent work by Fulton et al. (2017) demonstrated the presence of a deficit, or "gap", in the planet occurrence rate and provided a compelling observational motivation for invoking the photoevaporation of sub-Neptune atmospheres as a formation mechanism for super-Earths. There are also indications that close orbiting transiting planets are larger around young stars, further indicating possible photoevaporation (David et al. 2018). To improve our understanding of the processes that shape the bulk properties of small planets, we explore the relationships between radius, insolation, and density for exoplanets and small bodies in our solar system.

2. METHODS AND RESULTS

For this study, we used data from the NASA Exoplanet Archive and restricted the sample to confirmed planets with radius values $\leq$3.5 R$_\oplus$, augmented with recent results for the Trappist-1 system (Grimm et al. 2018). We removed two planets with anomalously large densities ($\rho > 20$ g/cm^3) and a planet pair with an anomalously large inclination difference, potentially indicating an unusual dynamical history (Rodriguez et al. 2018), resulting in a sample of 87 exoplanets. To divide the sub-Neptunes from the terrestrials, we used a value of 1.75 R$_\oplus$ (Lopez & Fortney 2014), which is also the approximate center of the occurance rate deficit identified by Fulton et al. (2017). Following Zeng et al. (2017) and Fulton & Petigura (2018), we used insolation as a proxy for the photoevaporation capability of the host star, and we estimated the insolation using the method of Weiss & Marcy (2014). In cases where the semi-major axis values were not reported, the values were estimated from the period assuming a circular orbit. The range of insolation for planets in this sample is greater than three orders of magnitude. When insolation is considered, we find that terrestrial planets separate into two families in the radius-insolation plane (see Figure 1), one with relatively lower levels of insolation (S/S$_\oplus$ < 10) and one with higher levels of insolation (S/S$_\oplus$ > 10), identified here respectively as the T1 and T2 families.

Interestingly, the separation of the T1 and T2 terrestrial planet families remains largely true in the radius-density plane. Additionally, photoevaporation of sub-Neptune (SN) H/He envelopes implies there should also be a connection between insolation and density. To explore that possibility, we constructed a radius-density diagram (see Figure 2 and also Figures 4 and 5). SN planets with radii > 1.75 R$_\oplus$ have lower levels of insolation than the T2 planets and are arranged as a consistent

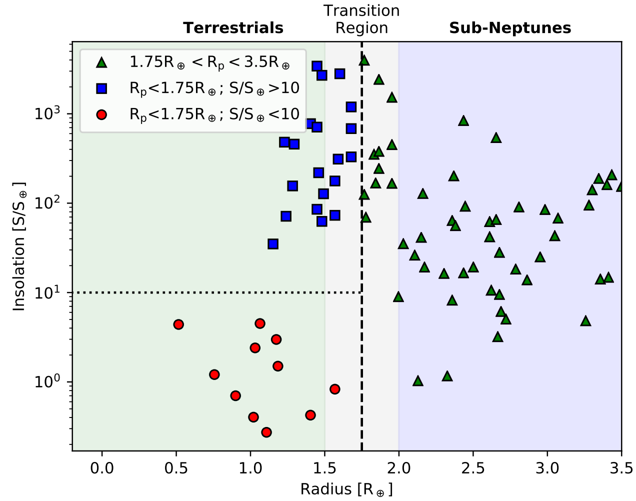

Figure 1. An insolation gap divides the terrestrial planets into two categories. This division has a good correspondence to trends in the density-radius plane, and we use it to define two families for terrestrial planets. The low and high insolation terrestrial families (red circles and blue squares respectively) are shown together with the sub-Neptunes (green triangles).

trend in the radius-density plane. For planets with radii 1.2 $R_\oplus$ <R< 1.75 $R_\oplus$ the average level of insolation increases.

If we temporarily exclude the T1 terrestrial family from consideration, a general trend emerges of increasing planet density with decreasing planet radius. We modeled this trend with a bilinear, piece-wise continuous function and retrieved the model posterior distributions using a Markov Chain Monte Carlo (Salvatier et al. 2016) method (see Figures 2 and 3). The average slope of the radius density function is larger for the T2 terrestrials (m_{T2}=-14.69$^{+1.02}_{-1.10}$) than for the sub-Neptunes (m_{SN} = -1.34±0.11. The T1 terrestrial family follows a completely different density-radius trend with density increasing as a function of radius. To probe the radius-density relationship between exoplanets and objects in our solar system, we assembled a list of 28 solar system bodies with reported densities and radii between 400 km $< R < R_\oplus$ (tabulated in the Appendix) that include terrestrial planets, moons, astroids, and trans-Neptunian objects. When these solar system bodies are included in the radius-density plane, they form a continuous population with the T1 family of low insolation terrestrial exoplanets, and we fit a linear model (m_{T1} = 4.58±0.49) to the radius-density function of this family (see Figure 2). This result for the density slope of the T1 exoplanets plus solar system bodies is very close to the prediction by Sotin et al. (2007) for terrestrial planets (see Figures 2 and 4) as having a density relation of $\rho = 5.51\ R/R_{Earth}^{0.65}$ and seems to confirm the classification of the T1 family as telluric planets.

Our results are qualitatively consistent with the density-radius trend reported by Weiss & Marcy (2014) but provide more detail and expand on the previous work in two important ways. First we incorporate the role of insolation and are thus able to identify specific subpopulations in the radius-density plane. Second, we are able to work with a significantly larger sample of both exoplanets and solar system objects. As we discuss below, this allows identification of two terrestrial planet families and a clearer picture of the sometimes competing, and sometimes complimentary, roles of collisions and photoevaporation in determining the properties of small planets.

3. DISCUSSION

The density-radius relation for small planets and small bodies is an important diagnostic of the physical processes participating in planetary formation and evolution. While the likely role of photoevaporation in converting sub-Neptunes into super-Earth terrestrial planets is obvious in Figure 4, the slope of the density-radius function in the different domains is revealing. To assist in the interpretation of these findings, we will discuss each of the planet family groups identified in the previous section (T1s, T2s, and SNs) as well as a "transition region" identified as 1.5 $R_\oplus$ <2.0 $R_\oplus$; the density-radius slope and average insolation values for the planet families and the transition region are tabulated in Table 1.

Type 1 Terrestrials: This family is characterized by comparatively low levels of insolation and a modest dependence of density on radius with an average slope m_{T1} = 4.58±0.49. A crucial aspect of this family is that it includes solar system terrestrial planets, exoplanet terrestrials, and solar system bodies that form a continuous trend in an insolation-selected, radius-density plane. Within the radius-density plane, terrestrial planets in our own solar system are intermingled with the exoplanets, suggesting a common formation mechanism. Terrestrial planets in the solar system are believed to have formed through impacts (Kokubo & Ida (1998); Schlichting et al. (2015); Genda et al. (2017) and references therein) and the continuity in the T1 family between exoplanets and solar system bodies with radii 400 km <R< $R_\oplus$ is a strong indicator that assembly by collisions is important. The apparent continuity of the trend raises the question of whether the T1 family is consistent with oligarchic growth scenarios (Kokubo & Ida 1998). The modest, positive slope for the T1 density-radius function probably reflects a combination of density enhancement through compression, as the size of the

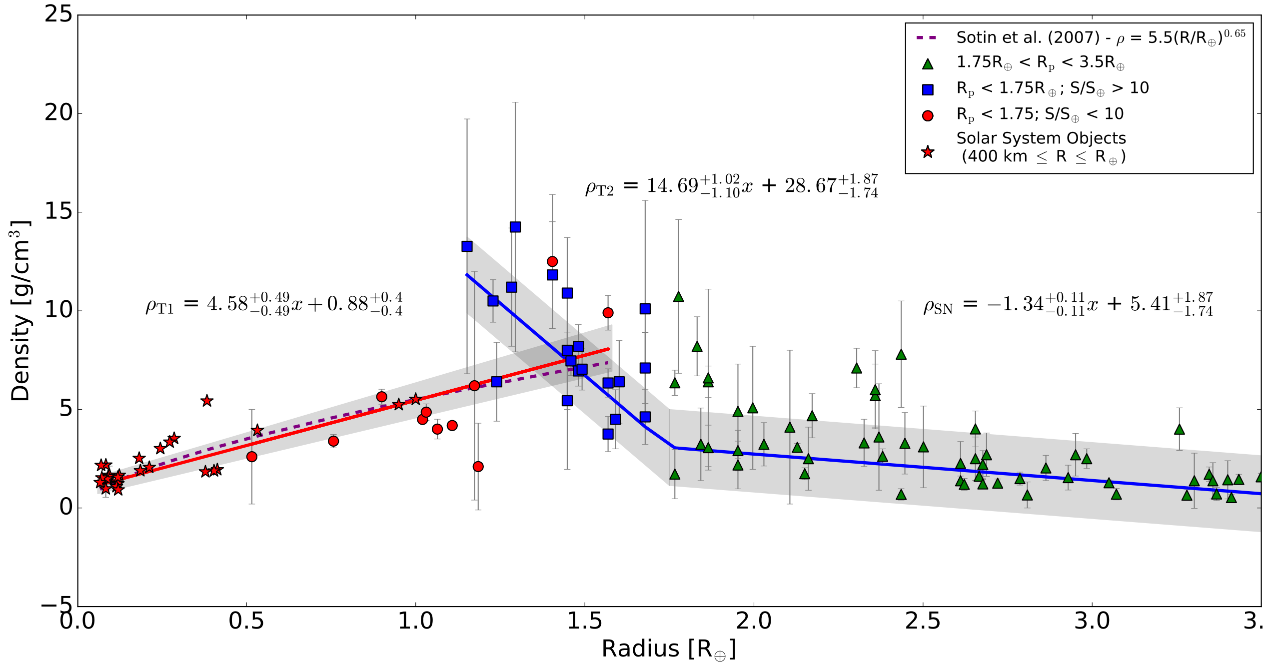

Figure 2. The results of a bilinear fit to the high-insolation T2 terrestrials (blue triangles) and sub-Neptune exoplanets (green squares). A negative slope is detected at the $> 5\sigma$ for both linear model components, implying photoevaporation is impacting planet density for both T2 terrestrial and sub-Neptune exoplanets. The low-insolation T1 terrestrial planets (red triangles) and solar system objects (stars) are fit with a linear model, which is in excellent agreement with previous theoretical modeling (dashed line) - see main body for further discussion. Data points are shown with $\pm 1\sigma$ uncertainties, and the grey areas denote the $\pm 1\sigma$ uncertainty regions for the linear models.

Table 1. Density-Radius Slope Results

Family/Region	Domain	Density-Radius Slope	Average S/S$_\oplus$
T1 terrestrials	R $<$ 1.75R$_\oplus$, S/S$_\oplus$ $<$ 10	$m_{T1} = 4.58 \pm 0.49$	0.8
T2 terrestrials	R $<$ 1.75 R$_\oplus$, S/S$_\oplus$ $>$ 10	m_{T2}=-14.69$^{+1.02}_{-1.10}$	743
sub-Neptunes	1.75 R$_\oplus$ $<$ R $<$ 3.5 R$_\oplus$	m_{SN} = -1.34 $\pm$0.11	250
transition region	1.5 R$_\oplus$R<2.0 R$_\oplus$	m_{TR} = -6.7$\pm$-1.9	773

bodies grows (Seager et al. 2007) and, potentially, loss of volatiles through collisions (Schlichting et al. 2015).

Sub-Neptunes: The pattern of increasing density with decreasing radius for the sub-Neptune family is consistent with modest levels of photoevaporation from 2.0 R$_\oplus$ $\leq$ R$\leq$ 3.5 R$_\oplus$ and the somewhat enhanced average insolation level in this region. If modest photoevaporation is, in a statistical sense, playing a role determining sub-Neptune density, it is removing of $\sim$ half the envelope mass ($\sim$1.5-3% of the total planet mass), corresponding to a typical sub-Neptune radius reduction of $\sim$ 35% for R$\sim$2.0 R$_\oplus$ or $\sim$ a quarter of the envelope mass, corresponding to a radius reduction of $\sim$ 20% for R$\sim$3.0 R$_\oplus$ (Lopez & Fortney 2014).

Type 2 Terrestrials: This family of terrestrial planets is characterized by high levels of insolation and a strong inverse dependence of density on radius with an average slope of the density-radius function of $m_{T2} = -14.69^{+1.02}_{-1.10}$. At the smallest radii for this family, density values are high, $\sim$ 10 g/cm^3. These are extremely large values for terrestrial planet density and some explanation is required. One possibility is that the decompression triggered by the evaporation of the atmosphere is not instantaneous Mocquet et al. (2014). However, the negative slope of the density-radius function implies that gravitational compression cannot alone be responsible for the high density values. Theoretical studies indicate that T2 planets likely have had the envelope completely stripped and are"bare cores" (Owen & Wu 2017). While the bare core scenario may not apply in the case of a secondary atmosphere established by mantle outgassing (Dorn et al. 2018) or delivered in the form of volatiles associated with accreted planetesimals (Elkins-Tanton & Seager 2008), the slope of the T2 density-radius function

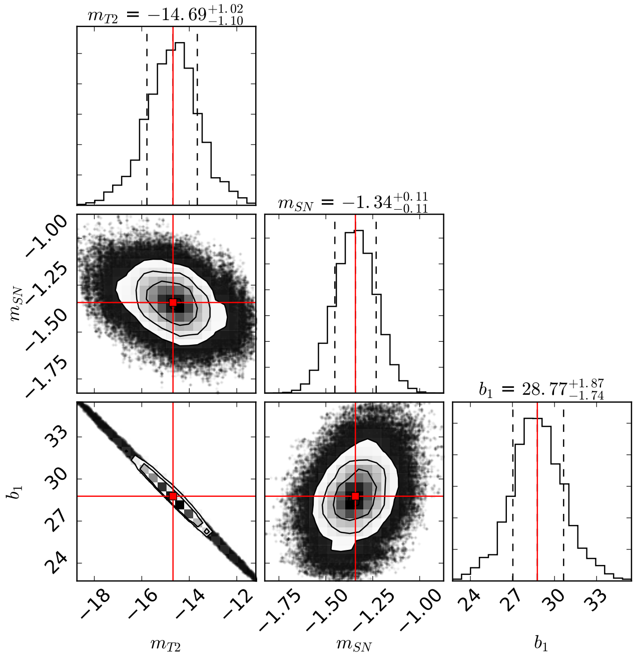

Figure 3. Correlation plots and marginalized posterior distributions for the model parameters. The mean values are indicated in red and the $\pm 1\sigma$ uncertainties are represented by the dashed lines.

is likely too steep to be consistent with these scenarios. Density enhancement of super-Earths by collisions has been studied (Marcus et al. 2009), and we suggest a modification of this scenario in which envelope-stripped bare cores have undergone a significant level of planetesimal bombardment early in the planet's history; the planetesimal impacts raise volatile plumes that are then efficiently stripped by the high-insolation levels. This scenario is consistent with the correlation between enhanced density and insolation that is present in this sample (see Figure 5) .

Impact driven atmospheric removal has been studied in the context of Earth (Schlichting et al. 2015) and is likely more efficient for the significantly higher levels of insolation associated with T2 planets. In our proposed secnario, the combination of planetesimal impacts on a bare core, in the presence of strong insolation, produces a fractional distillation type of effect where the heavy elements are preferentially retained, or reaccreted, and lighter materials are vaporized and then stripped. This process is more efficient when the gravitational binding energy is lower, which is consistent with the negative slope for the T2 density-radius relation. Further, the reaccretion of impact-produced siderophile elements has the potential to act as a reducing agent and transform atmospheric CO_2-H_2O into H_2 (Genda et al. 2017), further accelerating H loss and the density enhancement process. Work by Schlichting et al. (2015) shows this atmospheric loss process can also operate in the presence of an Earth-like atmosphere, implying that a bare core is not a requirement for a combined impact/photoevaporation-driven density enhancement process.

Transition Region: Following Lopez & Fortney (2014), this region corresponds to the range of radii (1.5 $R_\oplus \leq R \leq 2.0 R_\oplus$) associated with the transition from sub-Neptunes to super-Earths. In our sample, this region contains planets with densities that are indicative of sub-Neptunes and super-Earths and it also corresponds to the planet occurrence deficit identified by Fulton et al. (2017). The transition region spans the sub-Neptune-terrestrial boundary and also contains the highest average level of insolation of any part of the radius-density plane. Planets in this region, especially the lower density ones, offer the potential to observationally probe the process of envelope loss. The combination of T2 planets both inside and outside the transition region suggests there may be a wide diversity of timescales for envelope loss.

The T1, T2, and SN planet families, and the transition region, highlight the importance of stellar radiation, in either its presence or absence, on the formation and evolution of small planets. Fundamentally, there are three important axes (radius, insolation, and density) that allow identification of separate populations, and these have the potential to become confused when projected into 2-dimensional spaces. We illustrate this in Figure 2. Considering the identification of the separate populations in a 3-dimensional space allows informed speculation about whether the T1 and T2 populations merge. Our prediction is that, as more terrestrial-type planets are found, the T1 and T2 populations will *appear* to merge in a density-radius plot, but, in actuality, they will remain separate and fundamentally distinct populations in a radius-insolation-density space.

The initial identification of the T1 and T2 groups was based on insolation differences of planets with $R<1.75$ $R_\oplus$ but this single-parameter observational difference reflects a much more profound difference. While the T1 and T2 planet families can be termed terrestrial because of the combination of their radii and their bulk densities, which imply they must be rocky, their density-radius relation suggests that they have fundamentally different formation histories. Our contention is that T1 objects are assembled"from the bottom up" by a collisional process that assembles larger bodies from smaller pieces. Thus the T1 planets are truly Earth-like. In contrast, the T2 objects are ultimately produced from a "top down" evaporation of sub-Neptunes. Thus the

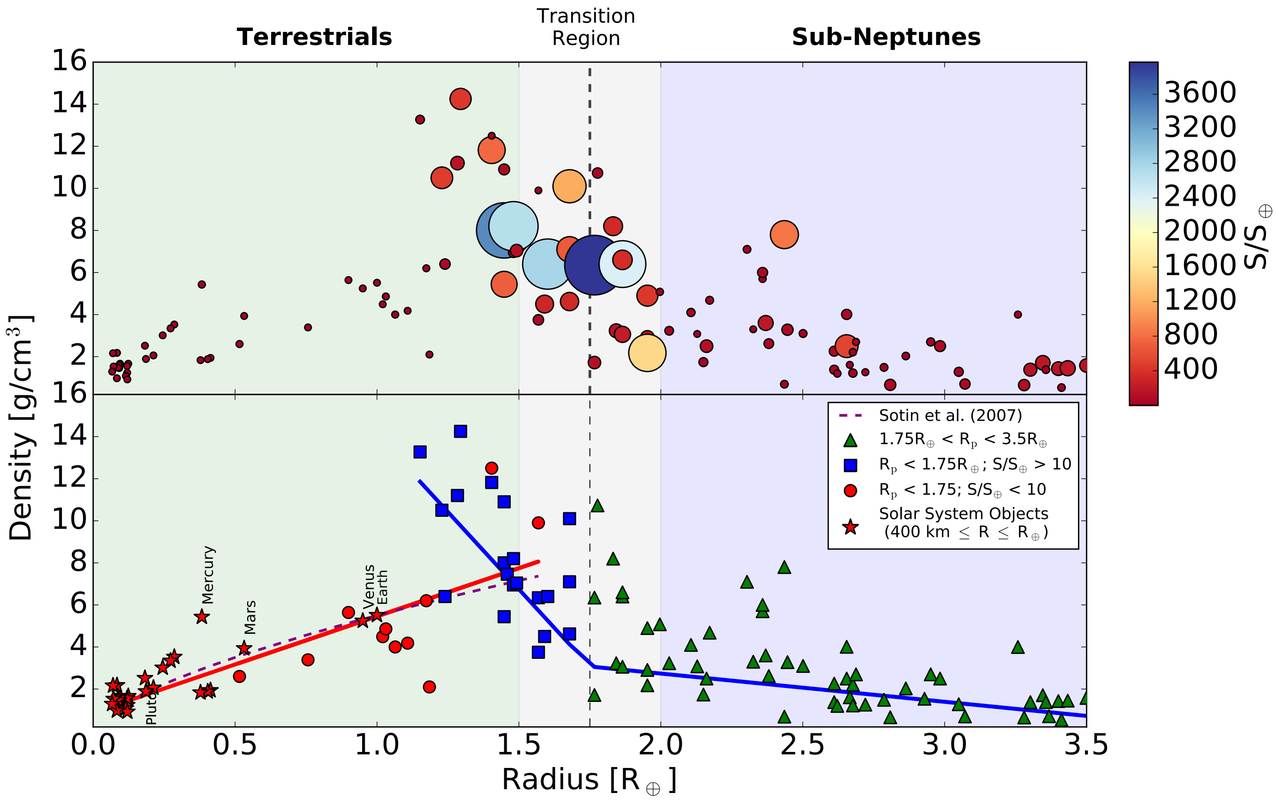

Figure 4. Distinct trends in the density-radius and density-insolation planes separate the T1 (low insolation - red circles) terrestrials and the T2 (high insolation - blue squares) terrestrials. Collisions likely enhance the density of both the T1 and T2 families, while photoevaporation is likely modifying the density of sub-Neptunes (green triangles) and creating the T2 family by complete envelope stripping of some sub-Neptunes.

T2 planets are the rocky core remnants of small gas giants that are linked to the photoevaporation of sub-Neptunes. In both the T1 and T2 objects, collisions likely play an important role of density enhancement through driving off volatiles. But photoevaporation has a completely unique role in the sculpting of the T2-SN density-radius relationship. If collisions do play a significant role in the density enhancement of some T2 objects, it implies their entire envelope formation and loss sequence happened extremely quickly, potentially allowing the super-Earth bare cores to undergo significant bombardment.

4. CONCLUSIONS

When considering a combination of exoplanets with known densities and radii 0<R< 3.5 R$_\oplus$, together with solar system bodies with known densities and radii 400 km <R< R$_\oplus$, and when considering insolation, we find the following. Terrestrial planets naturally divide themselves into two families that each form a continuous trend in the radius-density space. The T1 terrestrial family includes both exoplanets and the terrestrial planets and small bodies in our solar system. The density-radius-insolation relation for the T1 family is consistent

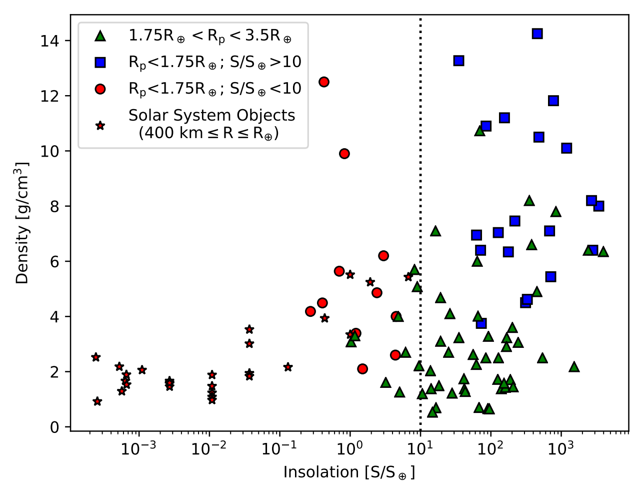

Figure 5. Enhanced levels of insolation are correlated with enhanced planet densities. The plot symbols are defined as in Figure 4.

with assembly of these bodies through collisions. Relatively low levels of insolation (< 10 S/S$_\oplus$) are characteristic of the T1 family.

A second terrestrial family, the T2 family is marked by relatively high levels of insolation, includes only exoplanets, and has a density-radius trend that is piece-wise continuous with the sub-Neptunes. The T2 density-radius trend implies that collisions, in the presence of strong photoevaporation, can create extremely high-density terrestrial planets ($\rho \sim 10$ g/cm^3). A high insolation transition region overlaps the junction between the T2 super-Earths and the sub-Neptunes. The sub-Neptune density-radius relation also shows evidence of modest photoevaporation. Taken together, the sub-Neptunes, transition region, and T2 super-Earths indicate the pervasive role of photoevaporation in sculpting a continuum from low density ($\rho \leq 1$ g/cm^3) planets with large H/He envelopes to extremely high-density terrestrials ($\rho \sim 10$g/cm^3). The strong implication is that T2 super-Earths are the remnant cores of small gas giant planets and were created by photoevaporative stripping of sub-Neptunes . The potential role of collisions in creating the high density T2 planets implies that the process of envelope assembly and stripping must be rapid for the highest density T2 planets, although the envelope stripping timescale could be much slower for T2 planets in the transition region.

Finally, we are in a position to provide an observations-based answer to the question posed in the introduction, "Are terrestrial exoplanets Earth-like, Venus-like, or the remnants of gas- or ice-giants?" Invoking the simplification that Earth-like and Venus-like are essentially the same, we can answer "both". Terrestrial planets apparently form from two mechanisms. One mechanism is "Earth-like" and relies on terrestrial planet formation by collisions. The other mechanism is through photoevaporation, which produces remnants of gas- or ice-giants.

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APPENDIX

Table of solar system bodies, with radius $R_\oplus$ to 400 km. This list of 28 solar system bodies with reported densities includes the terrestrial planets, moons, minor planets, asteroids, and trans-Neptunian objects. The majority of the density data is taken from the JPL Solar System Dynamics (SSD) database augmented by references in the literature when necessary. For objects that are planetary satellites, we use the planet semi-major axis for calculating insolation.

Body	**Mean Radius (km)**	**Mean Density (g/cm3)**	**Semi-Major Axis (au)**	**Citations**
Earth	6378.1366±0.0001	5.5136±0.0003	a_E	SSD
Venus	6051.8±1.0	5.243±0.003	a_V	SSD
Mars	3396.19±0.1	3.9341±0.0007	a_M	SSD
Ganymede	2631.2±1.7	1.942±0.005	a_J	SSD
Titan	2574.73±0.09	1.882±0.001	a_S	SSD
Mercury	2440.53±0.04	5.4291±0.0007	a_{Mer}	SSD
Callisto	2410.3±1.5	1.834±0.004	a_J	SSD
Io	1821.6±0.5	3.528±0.006	a_J	SSD
Moon	1737.5±0.1	3.344±0.005	a_E	SSD
Europa	1560.8±0.5	3.013±0.005	a_J	SSD
Triton	1353.4±0.9	2.059±0.005	a_N	SSD
Pluto	1188.3±1.6	1.89±0.06	a_P	SSD
Eris	1163±6	2.52±0.05	67.74049521464768±0.0027096	[1], SSD
Humea	797.5±5	1.89±0.08	43.3	[2], [3]
Titania	788.9±1.8	1.662±0.038	a_U	SSD
Rhea	764.30±1.10	1.233±0.005	a_S	SSD
Oberon	761.4±2.6	1.559±0.059	a_U	SSD
Iapetus	735.60±1.50	1.083±0.007	a_S	SSD
2007 OR10	767.5 ±112.5	0.92±0.46	67.37610770137752±0.0073504	[4], SSD
Charon	603.6±1.4	1.664±0.012	a_P	SSD
Umbriel	584.7±2.8	1.459±0.092	a_U	SSD
Ariel	578.9±0.6	1.592±0.092	a_U	SSD
Dione	561.70±0.45	1.476±0.004	a_S	SSD
Quaoar	535±19	2.18±0.43	43.69157469300723±0.0022972	[5], SSD
Tethys	533.00±0.70	0.973±0.004	a_S	SSD
Ceres	445.6±1.0	2.1620.0008	2.769165146349478±2.5823e-11	[6], SSD
Orcus	459±13	1.53±0.15	39.26631237879172±0.00090814	[5], SSD
Salacia	427±23	1.29±0.29	42.05690689579897±0.0056705	[5], SSD

Table 2. Semi-major axis values for the less commonly known solar system bodies are listed. For determining the insolation values of the moons, we use the orbit semi-major axis value for the parent body. The SSD site can be accessed at https://ssd.jpl.nasa.gov/. Reference key: [1] Sicardy et al. (2011), [2] Ortiz et al. (2017), [3] Rabinowitz et al. (2006), [4] Kiss et al. (2018), [5] Fornasier et al. (2013), [6] https://web.archive.org/web/20150905125337/http://nesf2015.arc.nasa.gov/sites/default/files/downloads/pdf/05.pdf.