**EXOPLANETS**

Density, not radius, separates rocky and water-rich small planets orbiting M dwarf stars

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Exoplanets smaller than Neptune are common around red dwarf stars (M dwarfs), with those that transit their host star constituting the bulk of known temperate worlds amenable for atmospheric characterization. We analyze the masses and radii of all known small transiting planets around M dwarfs, identifying three populations: rocky, water-rich, and gas-rich. Our results are inconsistent with the previously known bimodal radius distribution arising from atmospheric loss of a hydrogen/helium envelope. Instead, we propose that a density gap separates rocky from water-rich exoplanets. Formation models that include orbital migration can explain the observations: Rocky planets form within the snow line, whereas water-rich worlds form outside it and later migrate inward.

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Exoplanets that transit red dwarf stars (M dwarfs) intersect a large fraction of the stellar disk, making them potentially suitable targets for transmission spectroscopy (1). The habitable zones of planetary systems around M dwarfs are located close to the host stars, increasing the chance of transits occurring and shortening their period. Whether small planets around M dwarfs are potentially habitable remains unclear, in part because of incomplete knowledge of their composition (2).

Small exoplanets are known to have a bimodal radius distribution, with two populations separated by a gap, known as the radius valley (3). Potential explanations focus on atmospheric mass loss mechanisms, such as photoevaporation driven by the host star (4, 5) or due to the internal heating of the planet (6). Photoevaporation models can reproduce the position of the radius valley by assuming that super-Earth and sub-Neptune planets all have rocky compositions, with their different radii being a consequence of whether they retain their primordial hydrogen/helium atmosphere (H/He envelope). If the internal composition of these planets were icy, the radius valley would be at larger planetary radii (4, 7).

A purely rocky composition for most short-period small exoplanets is inconsistent with global formation models that include accretion and orbital migration mechanisms (8). These models predict that planets with masses below 20 Earth masses (M_⊕) become water-rich, because large-planet embryos are preferentially formed beyond the ice line (the distance from the central protostar where the temperature is cold enough for volatile molecules to condense into solid ice grains), and migration dynamics efficiently move objects in this mass range inward (9). These models reproduce other observed features of the small exoplanet population, such as the period ratio distribution of adjacent planet pairs and the overabundance of single-transiting systems (10). Those results were based on observations of planet radii alone. Knowing the density of each planet might provide more useful information, but this would require measurements of both mass and radius.

We investigated the population of small (planet radius less than 4 Earth radii, R < 4 R_⊕) transiting planets around M dwarfs (hereafter abbreviated STPMs). Determining the masses of planets observed in transit by space telescopes requires ground-based follow-up, with some STPMs having multiple inconsistent mass estimates in the literature. We compiled all published mass measurements for STPMs and used archival observations to refine the physical parameters of nine planets in seven planetary systems (table S8). We used the JULIET code (11) to model transits and radial velocities (12). To build our sample of STPMs, we began with the Transiting M-dwarf Planets catalog (13), which includes 43 planets with a radius smaller than 4 R_⊕ in 26 planetary systems as of 21 July 2021. We restricted our analysis to planets that are precisely characterized, requiring dynamical mass precision better than 25% and radius precision better than 8%. After our analysis of archival observations (12), 34 of the planets (80%) were considered to be precisely characterized by this definition.

Figure 1A compares our STPM sample with theoretical composition models (14) on a mass-radius diagram. We find that the planets do not form a continuum but are distributed in three separate populations. Two groups are consistent with specific compositions: the extrapolated mass-radius relation of Earth (hereafter rocky planets), and planets consisting of rock and water ice in 1:1 proportion by mass (hereafter water-rich worlds, or water worlds). The third group consists of planets with larger radii than either model, requiring H/He envelopes. We assigned each planet to the closest model composition, taking into account the uncertainties in mass and radius. In Fig. 1B, we show the same sample in a mass-density diagram, where the bulk densities of the planets have been normalized by a theoretical model of an Earth-like composition (scaled Earth’s bulk density, ρ_⊕, assuming mass fractions of 32.5% iron and 67.5% silicates) that accounts for gravitational compression (14).

The rocky population spans a large range of equilibrium surface temperatures (T_eq) and has a small dispersion in density. Many of these planets are close enough to their host stars to experience strong runaway greenhouse effects, so they are candidates to have extended atmospheres of water in a supercritical state (15, 16). With little liquid water on the surface, this increases the planetary radius relative to water-free planets (Fig. 2D). The population we identify as water worlds have almost constant bulk densities. These planets must have thin or nonexistent H/He atmospheres or supercritical water layers. Otherwise, small variations in the mass fraction of H/He envelopes (Fig. 2A) or in their temperatures (Fig. 2C) would result in large differences in the radius of the planets (14–16). Therefore, these planets aligned must be water-rich objects, not gas-rich.

The third population have radii larger than 2.5 R_⊕ and masses higher than 6 M_⊕. These are larger than rocky or water-rich planets of the same mass, so we refer to them as puffy sub-Neptunes. The nature of this population is more difficult to determine because interior and atmospheric composition models are degenerate. The possible scenarios include rocky worlds with massive H/He envelopes (Fig. 2A) or water worlds with thin envelopes (Fig. 2B), perhaps affected by a greenhouse effect that generates extended atmospheres of water in a supercritical state (16). However, there are no differences in T_eq between the water world and puffy sub-Neptune populations, and nearly all planets have T_eq > 400 K, high enough to potentially have inflated hydrospheres. Therefore, the larger radii dispersion of puffy planets could be a consequence of the individual H/He accretion histories, not atmospheric loss processes. If so, the water worlds and puffy sub-Neptunes could be part of a continuous population, with differences in their bulk densities arising from their different masses, which affect their accretion potential. Observations of water in the transmission spectra of the puffy sub-Neptunes K2-18 b (17, 18) and HD 106315 c (19) are consistent with this.
population is 0.94 ± 0.13 that the mean bulk density (radius) in each we fitted with Gaussian functions. We find density histograms for the STPM sample, which consisting of 50% water-dominated ices and 50% silicates (blue curve). In (A), planets are color-coded by their equilibrium temperature $T_{\text{eq}}$.

**Fig. 1. Sample of small transiting planets around M dwarfs (STPMs) as of 21 July 2021.** (A) Mass-radius diagram. (B) Mass-density diagram. Numerical values are provided in data S1 and include nine planets with revised masses and radii (table S8). Error bars show 1σ uncertainties on each measurement. In both panels, two theoretical composition models (J4) are plotted: an Earth-like composition (mass fractions of 32.5% iron and 67.5% silicates, green curve) and a planet that is consistent with our STPM sample (fig. S20). The simulations predict that water worlds are more common at lower stellar masses, with the minimum water world mass being a function of the host star mass. This has been attributed (26) to the migration of icy planets from beyond the ice line into the inner regions of the disk. Inward migration becomes efficient at lower planetary masses around lower-mass stars, which do not retain an envelope. For more massive stars, migration only occurs for planets above 10 $M_\oplus$, which are capable of accreting an envelope. Therefore, we propose that the observed population of planets around lower-mass M dwarfs includes more ice-rich cores, with low masses and without envelopes. Our finding of a minimum mass for water worlds of 2 $M_\oplus$ is also in agreement with simulations (26) for stellar host masses between 0.3 and 0.5 solar masses, which is the majority of our sample. We conclude that rocky planets formed within the ice line, whereas water worlds (as defined in Fig. 1) formed beyond the ice line and migrated inward. Our sample includes multiplanet systems with planets on either side of the radius valley. For those systems, we find that the innermost planet is always rocky and less massive, whereas the outermost belongs to the water world population (fig. S17).

For solar-type stars, which are higher in mass than M dwarfs, theoretical models predict
Fig. 2. Same as Fig. 1A, but for different internal composition models. (A) Earth-like rocky cores with H/He atmospheres by different percentages in mass at various temperatures ($14^\circ$). (B) Water-rich cores (50% Earth-like rocky core plus 50% water layer) with different mass fractions of H/He atmospheres at various temperatures ($14^\circ$). (C) Water worlds at different temperatures ($14^\circ$). (D) Models for Earth-like planets accounting for runaway greenhouse radius inflation ($15^\circ$).

Fig. 3. Normalized histograms of the STPM sample. Only planets that pass our precision requirements are included. (A) Frequency as a function of density divided by an Earth-like model. (B) Frequency as a function of planetary radius. Colors are as in Fig. 1B. Solid lines show Gaussian models fitted to the distribution of each planet type.
similar results. Based on mass-radius relations, the planets larger than the radius valley have been identified (14) as water worlds, and simulations using global planet formation and evolution models seem to support this hypothesis (27). The simulations produce a bimodal distribution of core mass and composition, which agrees with the observations. To explore whether our results can be extended from M dwarfs to solar-type stars, we attempted an analysis of known planets around F, G, and K-type stars. The results are shown in fig. S19. The planet distributions share some of the features of the STPM sample; however, the low number of precisely characterized small planets around these stellar types prevents us from drawing conclusions (12).

We conclude that STPMs can be classified into three groups using their bulk densities. All three planet types could potentially be habitable if the appropriate conditions are met (27–29). However, determining those conditions from observations requires knowing the composition of these small planets.

REFERENCES AND NOTES
1. H. Rauer et al., Astron. Astrophys. 529, A8 (2011).
2. A. Segura et al., Astrobiology 5, 706–725 (2005).
3. B. J. Fulton et al., Astron. J. 154, 109 (2017).
4. J. E. Owen, Y. Wu, Astrophys. J. 847, 29 (2017).
5. S. Jin, C. Mordasini, Astrophys. J. 853, 163 (2018).
6. S. Grunberg, H. E. Schlüterning, R. Sari, Mon. Not. R. Astron. Soc. 476, 759–765 (2018).
7. J. G. Rogers, J. E. Owen, Mon. Not. R. Astron. Soc. 503, 1526–1542 (2021).
8. S. N. Raymond, T. Boulet, A. Izidoro, L. Esteves, B. Bitsch, Mon. Not. R. Astron. Soc. 479, L81–L85 (2018).
9. C. Mordasini, Y. Albert, W. Benz, Astron. Astrophys. 501, 1139–1160 (2009).
10. A. Izidoro et al., Mon. Not. R. Astron. Soc. 470, 1750–1770 (2017).
11. N. Espinoza, D. Kosakowski, R. Brahms, Mon. Not. R. Astron. Soc. 490, 2262–2283 (2019).
12. See supplementary materials.
13. T. Trifonov et al., Science 371, 1038–1041 (2021).
14. L. Zeng et al., Proc. Natl. Acad. Sci. U.S.A. 116, 9723–9728 (2019).
15. M. Turbet et al., Astron. Astrophys. 638, A41 (2020).
16. D. Mousis et al., Astrophys. J. Lett. 856, L22 (2020).
17. A. Tsiaras, J. P. Waldmann, G. Tinetti, J. Tennyson, S. N. Yurchenko, Nat. Astron. 3, 1086–1091 (2019).
18. B. Benneke et al., Astrophys. J. Lett. 887, L4 (2019).
19. L. Kredberg et al., Tentative Evidence for Water Vapor in the Atmosphere of the Neptune-Size Exoplanet HD 106315 c. arXiv 2006.07444 (2020).
20. A. García Muñoz et al., Astrophys. J. Lett. 907, L36 (2021).
21. J. Venturini, G. M. Guidera, J. Haldeman, M. P. Ronco, C. Mordasini, Astron. Astrophys. 643, L1 (2021).
22. R. Cloutier, K. Menou, Astrophys. J. 853, 163 (2018).
23. R. Burn et al., Astron. Astrophys. Lett. 80, 23 (2020).
24. K. Lodders, Astrophys. J. 591, 1220–1247 (2003).
25. N. Brügger, R. Burn, G. A. L. Coleman, Y. Alibert, W. Benz, Astron. Astrophys. 640, A21 (2020).
26. R. Burn et al., Astron. Astrophys. 656, A72 (2021).
27. E. Bolmont et al., Mon. Not. R. Astron. Soc. 464, 3728–3741 (2017).
28. E. S. Kite, E. B. Ford, Astrophys. J. 864, 75 (2018).
29. N. Madhusudhan, A. A. A. Piette, S. Constantinou, Astrophys. J. 918, 1 (2021).
30. V. Van Eylen et al., Mon. Not. R. Astron. Soc. 507, 2154–2173 (2021).

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SUPPLEMENTARY MATERIALS
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Materials and Methods
Supplementary Text
Figs. S1 to S20
Tables S1 to S8
Data S1
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Fig. 4. Radius (A) and density (B) as a function of orbital period for the complete STPM sample. Planets are color-coded according to their bulk density, as in Fig. 1B. The dashed lines are previous determinations of the location of the radius valley (22, 30). The blue line and shaded region show our best-fitting model and its 1σ uncertainty, respectively, which are consistent with zero slope.