Helium worlds

https://doi.org/10.1038/s41550-025-02607-6

A new class of rocky exoplanets?

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Recent modelling suggests that Earth-mass planets in the habitable zones of Sun-like stars could evolve into rocky worlds topped by helium-dominated atmospheres.

The study of exoplanets is a humbling reminder of nature's creativity. As we uncover planets of various masses, sizes, and evolutionary paths, we are continuously challenged to revise long-held assumptions about what planets and their atmospheres can be. A new study by Lammer and colleagues[1] now pushes this paradigm shift even further, predicting that some Earth-mass planets in the habitable zones of Sun-like stars could host substantial, helium-dominated atmospheres. This result expands our expectations of rocky planets and may compel us to rethink how we search for habitable worlds.

The idea of helium-enriched atmospheres is not entirely new. In our Solar System, all giant planets contain roughly 10–20% helium by volume in their atmospheres. Beyond the Solar System, observations have revealed a large population of sub-Neptune-sized planets, many of which orbit much closer to their host stars than our own giants. Some of these planets may have atmospheres shaped by long-term mass loss. The concept of helium-dominated atmospheres emerged when Hu et al.[2] tried to explain puzzling early observations of the warm Neptune GJ 436 b (the observation itself is now called into question[3]) and proposed that, under certain conditions, a planet's hydrogen and helium envelope could evolve to become helium-rich over time. The key mechanism is elemental fractionation during atmospheric escape: since hydrogen is lighter than helium, it escapes faster. If this process continues long enough, a planet could be left with a residual helium atmosphere — a fossil remnant of its primordial envelope (Fig. 1).

Subsequent modelling has reinforced this idea. Malsky et al.[4] applied detailed planetary evolution simulations using the MESA code and found that helium enrichment is most likely on planets near the upper edge of the so-called 'radius valley', a gap in the exoplanet population that separates small, rocky planets from those with substantial volatile-rich envelopes[5]. Cherubim et al.[6,7] further demonstrated that extreme helium enrichment, leading to an atmosphere nearly devoid of hydrogen, could occur in planets with relatively long orbital periods. This prediction appears to be robust against variations in initial conditions and continuous exchange with the planetary interior. Generally speaking, one can understand these results by envisioning that the strong helium enrichment would be found on planets that are about to lose their entire hydrogen and helium envelopes. More importantly, detecting helium atmospheres for the predicted planet population would provide smoking-gun evidence for the interpretation that it was indeed the long-term evolution rather than initial formation conditions that gave birth to the apparent radius valley.

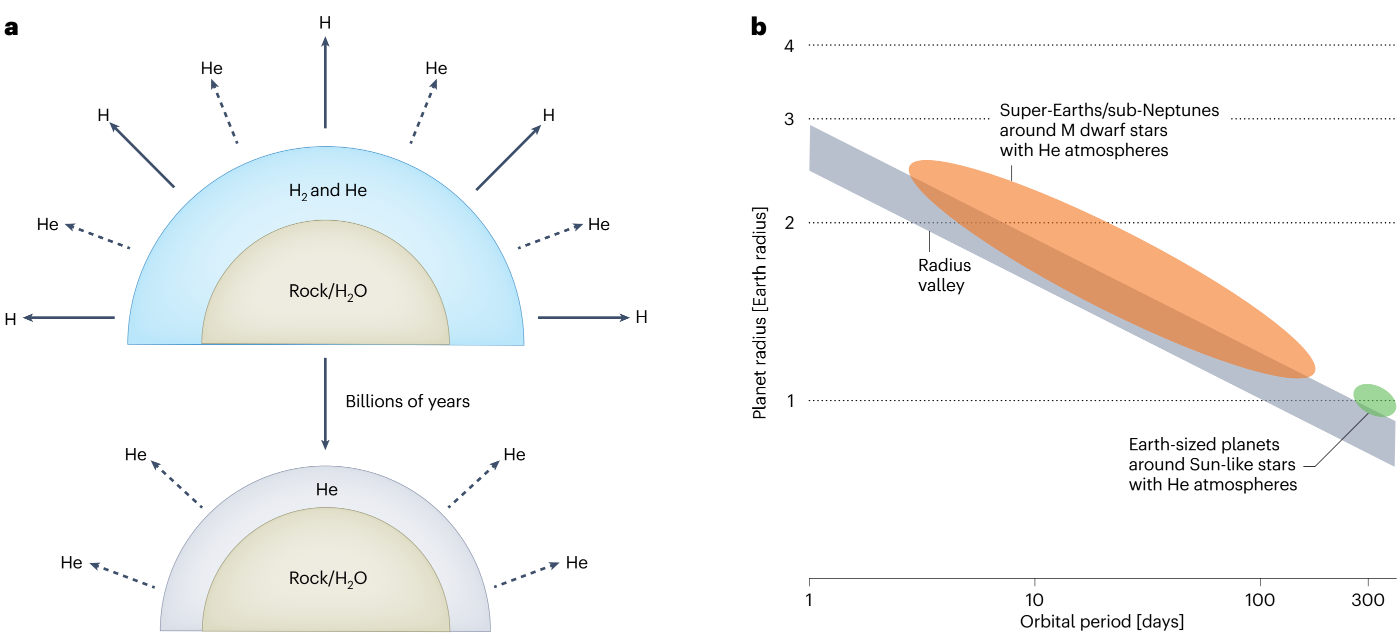

Fig. 1 | Helium atmospheres on small exoplanets. a, Atmospheric escape from small planets over billions of years can preferentially remove hydrogen from the primordial envelope, leaving behind a helium-dominated atmosphere (refs. 1,2,4,6,7; adapted from ref. 2). **b**, Helium worlds are expected to be found along the upper edge of the radius valley, in both planetary systems around M dwarf stars[6,7] and those around Sun-like stars[1]. Panel **a** adapted from ref. 2, The American Astronomical Society.

Lammer and colleagues now extend this concept to true rocky planets, showing that even Earth-mass planets could retain helium-dominated atmospheres over billions of years. Their work starts from a premise supported by planet formation models: that many Earth-mass planets may have formed with an initial hydrogen–helium envelope[8,9]. If so, Earth-sized planets in the habitable zones of Sun-like stars could follow a path where helium remains dominant after hydrogen is lost, according to simulations using a multispecies hydrodynamic model. Depending on the evolution of the host star, larger planets would retain both hydrogen and helium and smaller planets would lose both gases — but a narrow mass range that straddles Earth's mass could see only helium retained. These helium atmospheres could be a few bars to hundreds of bars thick, and they are remnants of the primordial envelope rather than a byproduct of radioactive decay as one might imagine for rocky planets.

The implications of this prediction are profound. Extrapolating the radius valley — originally derived from the demographics of shorter-period planets — to longer-period planets suggests that Earth-sized planets in the habitable zones of Sun-like stars may also align with the upper edge of this valley (Fig. 1). This implies that atmospheric evolution could be a unifying mechanism shaping a broad spectrum of small exoplanets. For planets that retain helium, ongoing helium escape could produce observable spectral signatures in absorption lines near 1 μm if the planets transit their host stars[10]. Detecting such signatures would provide a crucial observational test for the helium-world hypothesis and offer direct insight into the atmospheric evolution of small, potentially habitable planets.

If helium atmospheres are indeed common among rocky, long-period exoplanets, then our search for Earth-like worlds must account for the possibility that many small planets in the habitable zones of Sun-like stars may look nothing like Earth. While a helium atmosphere could still support habitability in some form, its properties and appearance would be distinct. For example, helium has a lower heat capacity than nitrogen or carbon dioxide, potentially leading to different atmospheric temperature profiles and cloud structures. Meanwhile, helium, unlike hydrogen, behaves as an inert background gas, meaning that a helium-dominated atmosphere could still contain any abundances of CO_2, H_2O, and other key species relevant to habitability. This work adds to a growing body of evidence suggesting that rocky planets in the habitable zone may follow a wide range of evolutionary paths[7,11]. In our quest for Earth 2.0, we may need to embrace the possibility that it will be, in many ways, entirely unlike Earth.

Aside from exoplanets, this revelation prompts new questions about the evolution of Earth itself. If our planet was once shrouded in hydrogen and helium, how did we escape a helium-dominated fate? Lammer and colleagues argued that Earth did not finish forming when the protosolar disk dissipated, and any initial hydrogen and helium was quickly lost. But some recent theories suggest that, if the newly formed Earth had a hydrogen envelope, it would interact with its interior through a magma ocean and contribute to the formation of water oceans and a lower-density core[12], while the light elements in Earth's core are uncertain[13]. In this picture, why did the helium not persist? Was it blown away by the Moon-forming impact, or was it sequestered in some yet-unrecognized processes? These questions underscore how exoplanet studies continuously reshape our understanding of planetary evolution, including that of our own world.

As we enter the era of detailed characterization of smaller and cooler exoplanets, helium worlds present an intriguing opportunity. Advanced telescopes, including JWST and its successors, could be used to detect helium-rich atmospheres and test these predictions. If confirmed, these discoveries would reveal new classes of planets — helium-rich sub-Neptunes and rocky planets with helium-dominated atmospheres — that challenge our preconceptions of habitability and planetary evolution. The diversity of small planets may be far greater than we imagined, and the most exciting discoveries still lie ahead.

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Published online: 2 July 2025

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Acknowledgements

The author thanks R. Wordsworth, C. Cherubim, I. Malsky, A. Bello-Arufe, and M. Zilinskas for helpful discussions. This article was written at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

Competing interests

The author declares no competing interests.