

Liquid water on planets with a primordial atmosphere can be long-lasting

Super-Earths that retain their primordial atmospheres can have long-lasting temperate surfaces. If a layer of water can form on such a planet, it could be liquid for billions of years.

This is a summary of:

Mol Lous, M. et al. Potential long-term habitable conditions on planets with primordial H–He atmospheres. *Nat. Astron.* <https://doi.org/10.1038/s41550-022-01699-8> (2022)

Published online:

27 June 2022

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

The question

In the search for liquid water outside of the Solar System, it should be considered that water can form on planets that are very different from Earth. One proposed unconventional scenario is when a planet retains the atmosphere it accreted from the protoplanetary disk¹. Such a primordial atmosphere is dominated by hydrogen and helium, with the former causing a greenhouse effect that leads to warming of the planet's surface and gets stronger with increasing pressure. The lightweight hydrogen molecules are more likely to be retained for planets that evolve far from the host star, where stellar radiation is insufficient to cause them to escape. These planets would not need stellar radiation to be warm enough for liquid water to exist; instead, they can rely solely on their intrinsic heat. Evolutionary processes such as atmospheric escape (the loss of atmospheric gases to outer space) and heat loss from the core of the planet should thus be combined to study this potential habitat and investigate the existence and stability of liquid water.

The discovery

We used computational evolution models to study how the planetary surface conditions change over time to determine the duration for which liquid water can exist. The stellar radiation (we assume a Sun-like star) increases with time, whereas the intrinsic heat from the core weakens. There are therefore ideal combinations of properties that allow for the longest duration of liquid water. The properties we considered are the core mass, the envelope mass (that is, the mass of the gaseous atmosphere) and the star–planet separation. We included an intrinsic luminosity model that depends on the core mass and envelope mass, and applied different models of atmospheric escape. Moreover, we investigated the sensitivity of the results to the model parameters.

Our results show that surface pressures and temperatures that allow for liquid water last for >5 billion years on planets with an envelope mass of ~0.01% of the Earth's mass (with surface pressures of 100–1,000 bar) (Fig. 1). However, envelopes that are an order of magnitude larger (smaller) allow for long-term liquid water when the planet

is farther away from (closer to) the star. The duration of liquid water can far exceed 5 billion years for planets that are solely heated by their interior, owing to the timescale of radioactive decay. Planets with a small envelope that orbit close to the star lose their whole envelope to hydrodynamic escape (one of the atmospheric escape models we considered); hence, the lack of data points in the bottom-left corners of the plots in Fig. 1. Indeed, we do not find long-term liquid water to be possible within star–planet separations of 2 AU. Furthermore, we show that scaling parameters (such as the intrinsic luminosity or the composition of the gaseous atmosphere) change the ideal envelope masses but do not change the size of the parameter space in which long-term liquid water is possible.

Future directions

The idea that liquid water could exist underneath a primordial atmosphere is not new¹. However, so far, only a few studies have focused on this concept of 'alternative habitable conditions'^{2–5}. This planetary type clearly deserves further attention, especially as observations show that the Solar System is not necessarily a typical planetary system. Our results strengthen the case for considering planets very different from Earth when investigating potential habitability. Liquid water is seen as an important, if not vital, criterion for habitability. That planets with a primordial atmosphere could provide stable conditions for liquid water on such a long timescale is something we hope will be considered by exoplanet researchers and astrobiologists.

Our model is relatively simple. This enabled us to explore a large parameter space in the evolution models. Interactions between the interior, water and atmosphere were not taken into account but are important and should be studied in the future. These interactions might further constrain the planets on which liquid water is possible.

The next step is to investigate the formation likelihood of planets that have the right initial conditions for long-lasting liquid water. This information will allow us to estimate how often we can expect such a planet to occur.

Marit Mol Lous^{1,2}

¹Universität Bern, Bern, Switzerland.

²Universität Zürich, Zürich, Switzerland.

EXPERT OPINION

|| This work explores the potential habitability of planets with hydrogen-dominated atmospheres that are located outside the habitable zone defined for Earth-like (that is, carbon dioxide–nitrogen–water) atmospheres. The simulations are extensive and offer a near-complete

exploration of hydrogen-dominated habitability. Given that the parameter space for surface liquid water is expanded by the presence of hydrogen, planets outside the conventional habitable zone could also be habitable. The authors have done an excellent job.” **An anonymous reviewer.**

FIGURE

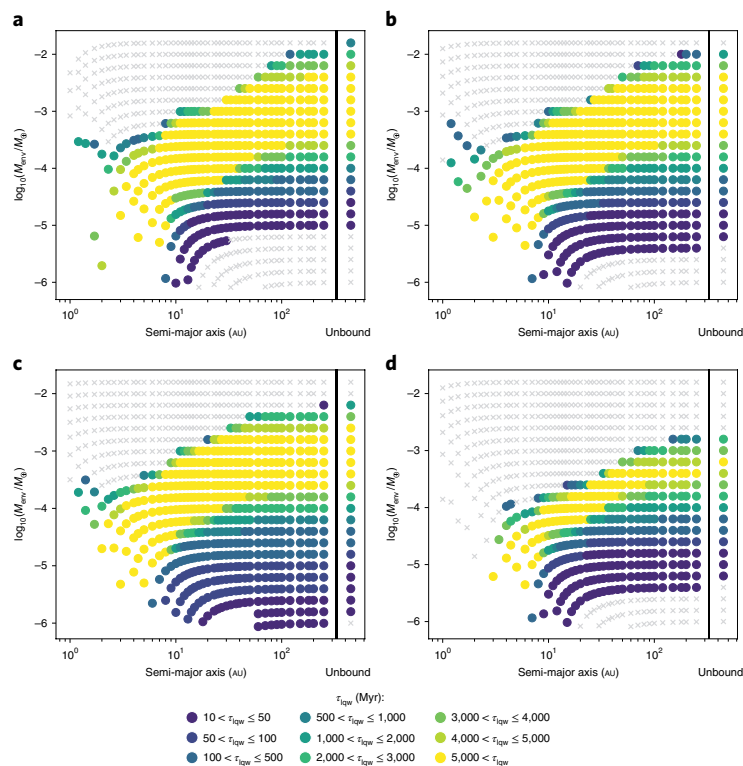


Fig. 1 | Duration of conditions for liquid water. a–c, Duration of surface temperature and pressure conditions for liquid water (τ_{liq}) on planets with core masses of 1.5, 3 and 8 Earth masses (M_{\oplus}), respectively. The separation between the planet and the star is varied (x axis) as well as the mass of the envelope (M_{env} ; y axis). d, Results for planets with a core mass of 8 M_{\oplus} , but with the restriction that the surface temperature is <400 K, which is an estimated upper limit for the chemistry of life. Unbound planets that do not receive any stellar radiation are also considered. © 2022, Mol Lous, M. et al., [CCBY 4.0](https://creativecommons.org/licenses/by/4.0/).

BEHIND THE PAPER

In April 2020, we started to work on this project. I was hired as a shared PhD student between the University of Bern and the University of Zürich. From the beginning, the goal of the project was to study whether liquid water can exist on planets very different from Earth. More specifically, we wanted to continue on the work already done for planets with a primordial atmosphere.

The project started almost exactly at the same time that the COVID-19 pandemic hit Europe, which of course came with its challenges. It took several months of working together virtually before we got to meet each other in real life. Luckily, we can now continue working on this project in better circumstances, and are again able to have spontaneous meetings and scientific discussions. **M.M.L.**

REFERENCES

1. Stevenson, D. J. Life-sustaining planets in interstellar space? *Nature* **400**, 32 (1999). **This paper was the first to calculate that collision-induced opacities of hydrogen can cause a greenhouse effect strong enough to allow for liquid surface water.**
2. Pierrehumbert, R. & Gaidos, E. Hydrogen greenhouse planets beyond the habitable zone. *Astrophys. J. Lett.* **734**, L13 (2011). **This paper discusses the relationship between stellar radiation and the ideal envelope mass of hydrogen in order to have liquid water.**
3. Wordsworth, R. Transient conditions for biogenesis on low-mass exoplanets with escaping hydrogen atmospheres. *Icarus* **219**, 267–273 (2012). **This paper examines the link between atmospheric escape and the longevity of liquid water conditions.**
4. Seager, S. Exoplanet habitability. *Science* **340**, 577–581 (2013). **A review article that proposes a new ‘habitable zone’ for planets with hydrogen–helium-rich atmospheres.**
5. Madhusudhan, N. et al. Habitability and biosignatures of Hycean worlds. *Astrophys. J.* **918**, 1 (2021). **This paper investigates several properties of planets with liquid water underneath a hydrogen–helium atmosphere, such as the possible mass–radius relationships.**

FROM THE EDITOR

|| There is currently an intense debate on what makes a planet habitable and how to define habitability. This paper adds an important contribution to the discussion, studying the long-term perspectives for liquid water of terrestrial planets with hydrogen atmospheres. These planets sound very exotic to us, but could be quite common in the Universe.” **Luca Maltagliati, Senior Editor, Nature Astronomy.**