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.

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 disk. 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 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 new. However, so far, only a few studies have focused on this concept of ‘alternative habitable conditions’. 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.

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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 defined for Earth-like (that is, carbon dioxide–water) atmospheres. The simulations already done for planets with a primitive atmosphere. 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.

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 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.

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