Redox state and interior structure control on the long-term habitability of stagnant-lid planets

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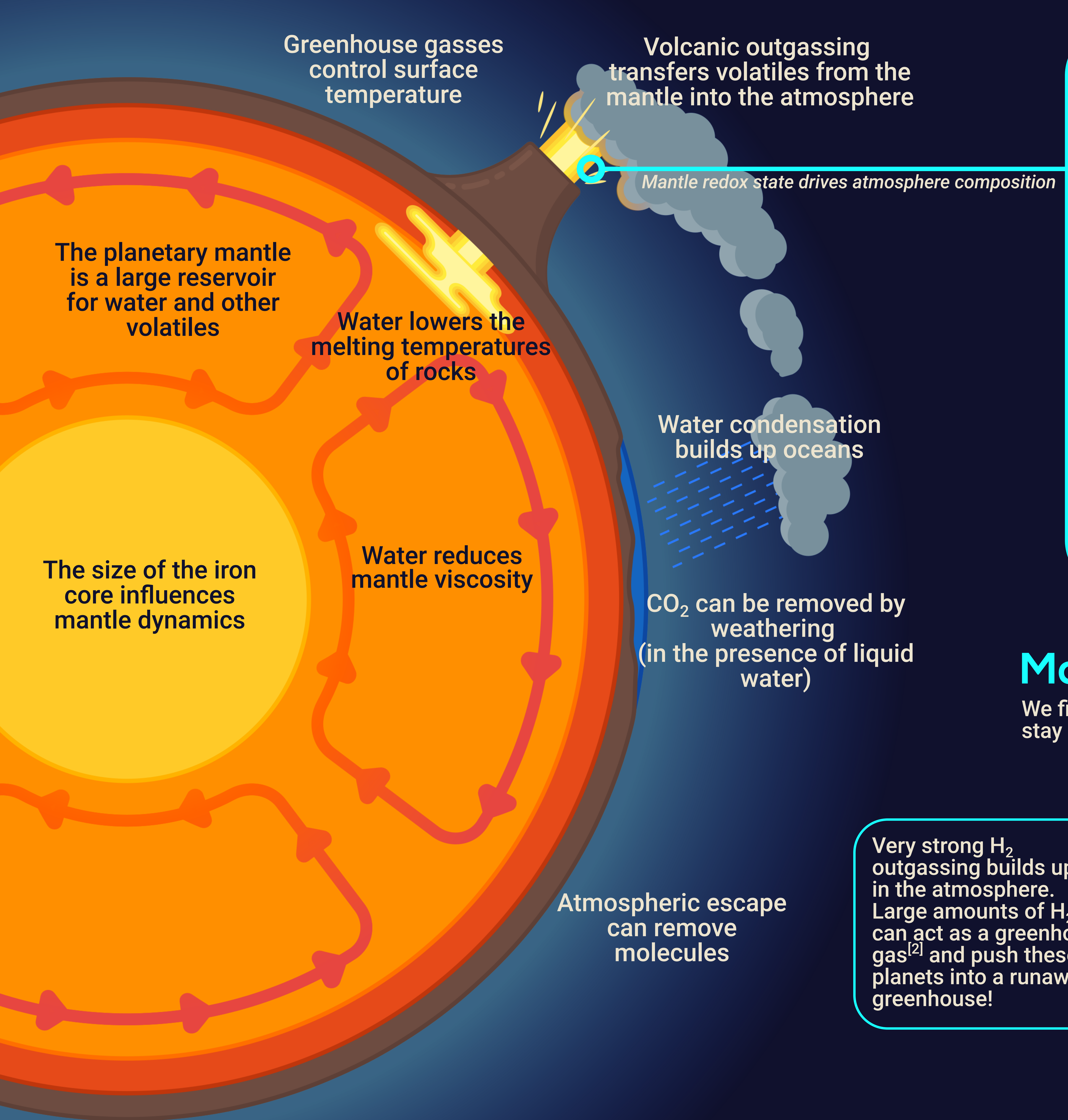
Habitable planets

For a planet to support life, the temperature and pressure at the surface need to allow the existance of liquid water, and these conditions must be stable over geological timescales. Volcanic outgassing continuously changes the atmosphere, so not every planet in the habitable zone may actually be habitable.

Which parameters of the planet interior are important for habitability?

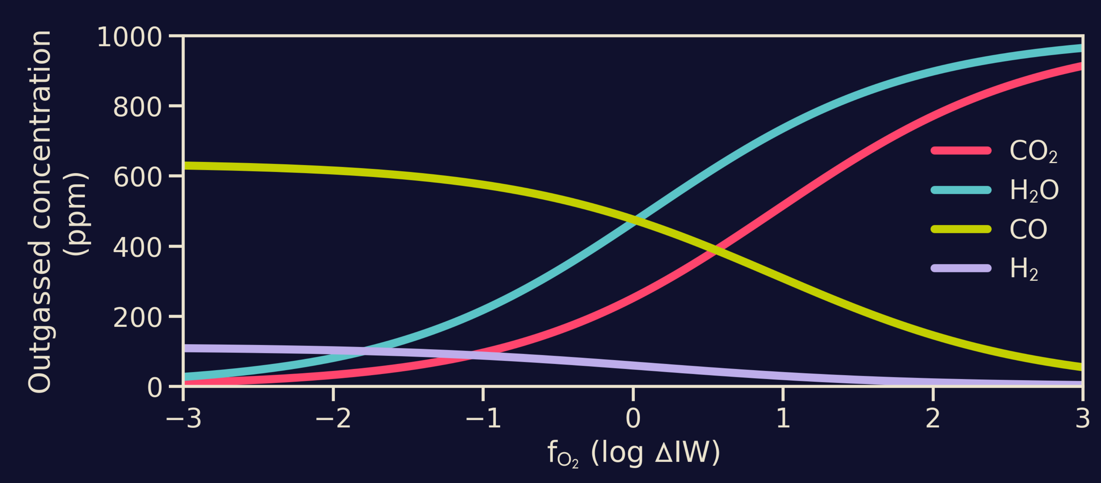
Interior-atmosphere feedback processes

The atmosphere and the interior of planets are not separate systems, but instead coupled via various feedback mechanisms. On planets without plate tectonics (stagnant-lid), volcanic outgassing acts as the primary link between atmosphere and interior. Water in particular plays a large role in both interior and atmosphere.
Some of the most important processes are illustrated below:



Outgassing chemistry

Which species are actually outgassed depends on the redox state of the planet's mantle (determined by the oxygen fugacity f_{O2}) and the current atmosphere composition:
At oxidizing conditions, oxygen-rich species such as H_2O and CO_2 are outgassed. At reducing conditions, oxygen-poor species like H_2 and CO become important.
We use a model from Ortenzi et al. (2020)[1], which calculates the equilibrum chemistry between melt and atmosphere in in the C-O-H system.



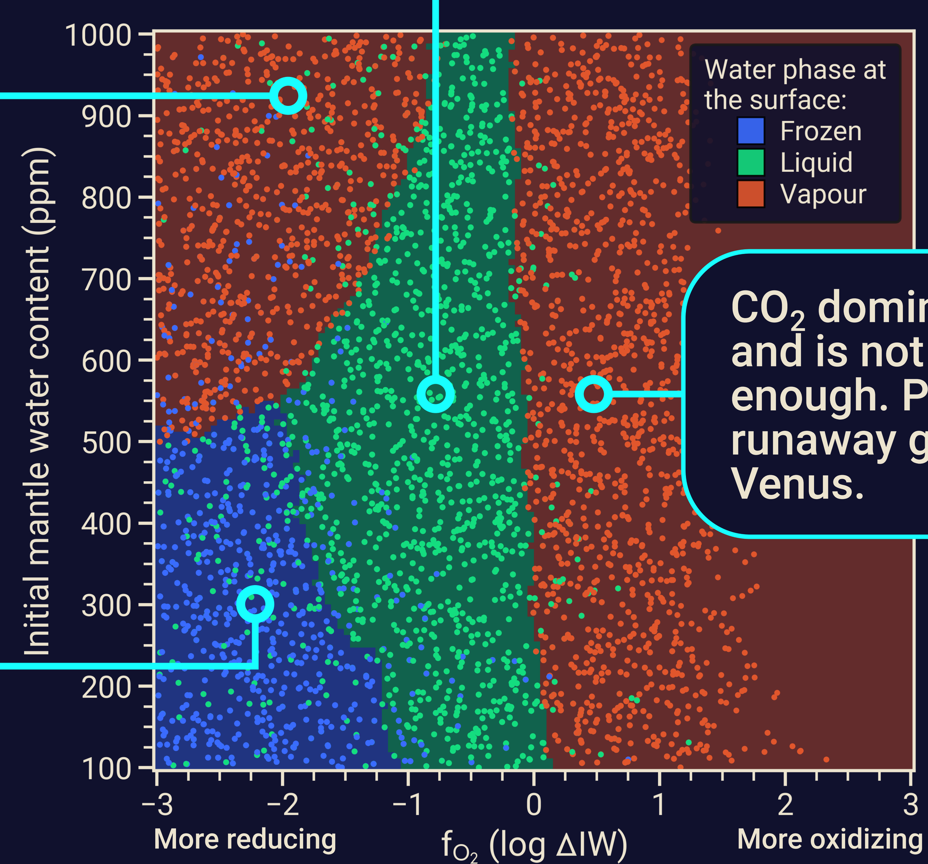
Example of the composition of outgassed species as a function of oxygen fugacity. The exact outgassed composition depends also on the current atmospheric composition, surface pressure, melt temperature, and water content in the melt.

Mantle redox state drives habitability

We find that the redox state of the mantle is a determining factor if a planet can stay habitable over geological timescales.

Very strong H_2 outgassing builds up H_2 in the atmosphere. Large amounts of H_2 can act as a greenhouse gas[2] and push these planets into a runaway greenhouse!

CO_2 outgassing is just high enough to keep the planet from freezing, but excess CO_2 can be weathered away. These planets are habitable for billions of years!



CO_2 dominates outgassing and is not removed fast enough. Planets end up in a runaway greenhouse similar to Venus.

Very little CO_2 outgassing, and volcanic activity is low due to water-poorer mantles. These planets remain below the freezing point of water for most of their evolution.

Each point in the figure represents an Earth-analogue with a different mantle oxygen fugacity and water content at a random age. The color of each point shows the phase at which water exists at the surface.
The background marks the region where most points share the same conditions.

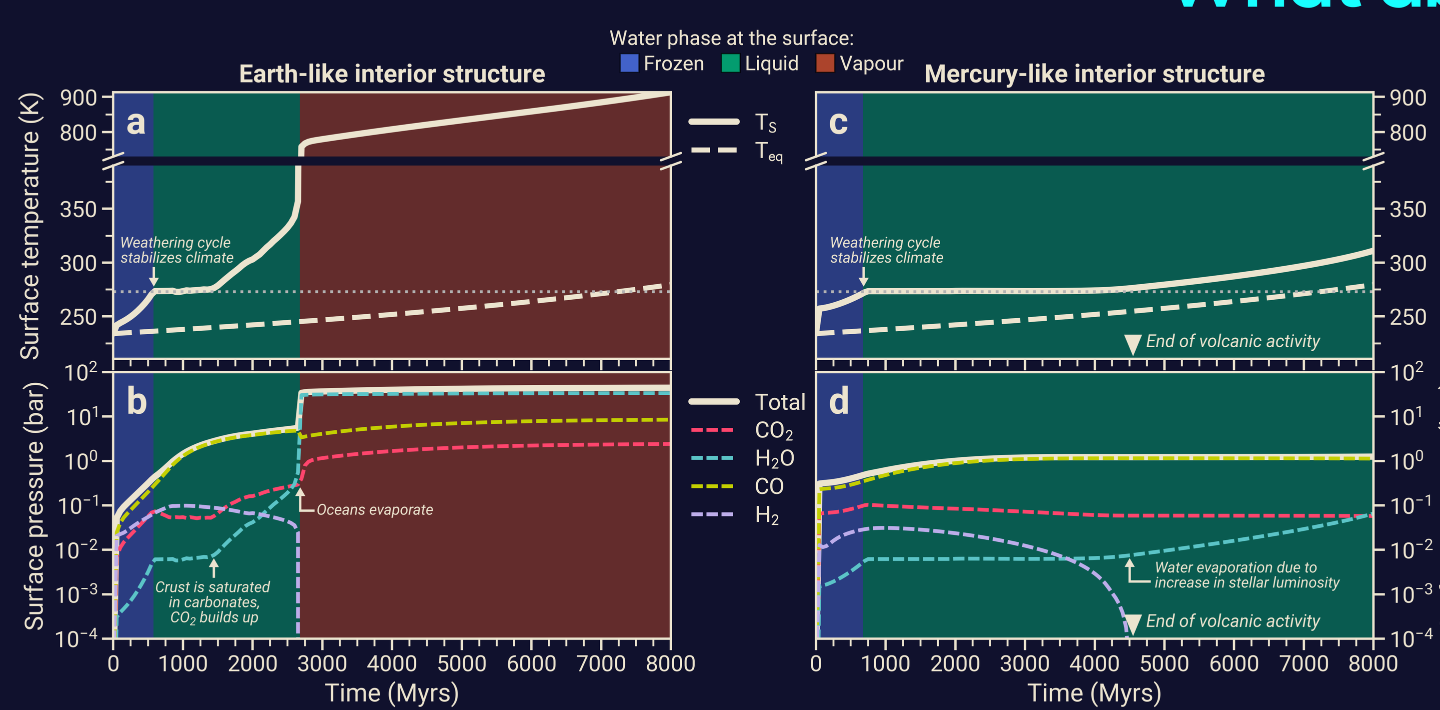
Our modeling approach

We use a 1D mantle convection model to simulate the coupled evolution of the interior and atmosphere of more than 200 000 planets around Sun-like stars over 8 Gyrs. We include a comprehensive number of significant feedback processes. The surface temperature and pressure is determined with a two-stream gray atmosphere model

For each planet, we randomly set the oxygen fugacity of the mantle between -3 to 3 log-units around the IW buffer and the water content of the mantle between 100 and 1000 ppm.

We investigated the emergence of habitable conditions for following parameters:
- Planet mass (up to 3 $M_\oplus$)
- Iron core size (between 30% and 70%)
- Orbital distance (from Venus orbit to Mars orbit)

What about the interior structure?



Planets with large iron cores (similar to Mercury) tend to have less volcanic activity. Their thin mantles cool faster, and less melt reaches the surface due to high gravity gradients[3]. This limits the build-up of CO_2 in the atmosphere, and helps to prevent a runaway greenhouse in many cases. This allows many of these planets to be habitable much closer to their host star.

These plots show the temperature and pressure evolution of the atmosphere of an Earth-mass planet with an Earth-like core radius (54.5%) compared to a planet with a Mercury-like core (70%). Otherwise, both planets share the same set of parameters (oxygen fugacity, initial mantle water content, orbital distance).

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References

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[3] Noack, L., Rivoldini, A. & Van Hoolst, T. Volcanism and outgassing of stagnant-lid planets: Implications for the habitable zone. Physics of the Earth and Planetary Interiors 269, 40–57 (2017).