EPSC Abstracts
Vol. 17, EPSC2024-425, 2024, updated on 29 Apr 2025
https://doi.org/10.5194/epsc2024-425
Europlanet Science Congress 2024

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

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The James Webb Space Telescope has ushered in the age of exoplanet atmosphere characterization. Not only is it possible for the first time to detect atmospheres on rocky exoplanets, the spectral analysis of the atmosphere allows a compositional characterization of the major gas species. This holds the promise of gaining insight into the interiors of exoplanets and their mineralogical make-up, which are otherwise hidden from view.

The atmosphere and interior of a rocky planet do not form separate systems, but are coupled by an intricate network of feedback processes which link the evolution of the atmosphere to the evolution of the interior, and vice-versa. In particular, volcanic outgassing of volatile species from the planet's silicate mantle shapes the atmospheric composition, temperature, and pressure, but the exact composition of outgassed species not only depends on the volatile content and oxidation state of the mantle, but also on the current state - i.e., pressure, composition, and temperature - of the atmosphere. In particular, many feedback loops rely on (or are influenced) by the presence of water: The climate-stabilizing carbonate-silicate cycle depends on an active water cycle for the weathering of silicates, i.e. surface temperatures which permit liquid water. The presence of liquid water is a necessary precondition for the development of life. Water in the form of hydrous minerals significantly influences the convection dynamics of the mantle by lowering the viscosity and melting point of rocks, promoting more vigorous convection and volcanic activity, which in turn drives the atmospheric evolution. An understanding of the interplay of these processes is necessary to interpret observed exoplanet atmospheres and to quantify the necessary planetary properties which lead to the emergence of habitable conditions.

Here, we explore the diversity of atmospheres that may emerge on stagnant-lid exoplanets — those without plate tectonics — and identify the parameters which lead to the emergence of habitable conditions. Our investigation includes various key parameters, such as planet mass, the size of the iron core, the oxidation state and water content of the mantle, as well as the distance of the planet to its host star. We use a 1D numerical model to simulate the coupled evolution of the interior and atmosphere. We include a comprehensive array of feedback processes and interactions between interior and atmosphere, such as a CO2 weathering cycle, volcanic outgassing, a water cycle between ocean and atmosphere, greenhouse heating, as well as escape processes of H2. While many atmosphere-interior feedback processes have been studied before in detail, we present here a comprehensive model combining the important planetary processes across a wide range of terrestrial planets.

The modeling of more than 280 000 coupled atmosphere-interior evolutions shows that a wide diversity of atmospheric compositions develops in response to interior properties, in particular driven by the oxidation state of the mantle and its water content. Only a narrow range of mantle oxidation states allows long-term habitable conditions, and many planets with oxidized mantles end up with Venus-like hot, dense atmospheres instead. On the other hand, on planets with more reducing mantles, the amount of outgassed greenhouse gasses is often too low to keep the surface above the freezing point of water.