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Chemical exchange in the interior of water-rich exoplanets

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Abstract

Since the discovery of the first exoplanet in 1995 [1], the number of detected exoplanets has grown nearly exponentially [2]. We have learnt from the existing dataset that our Solar System is rather unusual. Exoplanet surveys revealed notably that exoplanets intermediate between Earth and Neptune are surprisingly common, while notably absent in the Solar System [3]. Model mass-radius relationships indicate a great diversity of interior composition and atmospheric extent for the Super-Earth/Mini-Neptune-planet class [e.g. 4].

The observed continuum between Earth-sized and Neptune-sized planets challenges our understanding of planet formation and evolution, which has been biased for many years by our vision of the Solar System. Planetary worlds are probably much more diverse than originally thought, with a wide range of water and other volatile content. In the Solar System, there is a strong dichotomy between the inner system with dry planetary objects having a very small volatile fraction (<0.1 %), and the outer solar system where water ice constitutes a large fraction of solid phase (> 20%). The volatile contents among other systems likely vary more gradually, and a large fraction of exoplanets with sizes intermediate between Earth and Neptune may have a water content exceeding several percents.

The existence of massive water envelops around these planets may significantly affect the internal evolution and chemical exchanges between the deep interior and the atmosphere [e.g. 5]. Due to the very high-pressure expected inside these water-rich planets, especially for the most massive ones, most of the water will be in the form of a high-pressure ice phase (ice VII) [6,7], the presence of liquid water being limited only to the first kilometres. The thermal structure and dynamics of these thick icy mantles are expected to control the heat and chemical transport from the silicate-rich interior to the surface [8,9], in a way analogous to the internal processes expected inside large icy moons like Titan and Ganymede [10]. At the temperature and pressure ranges expected in these thick icy mantles, most of volatile compounds are expected to be in a solid state, either trapped as clathrate hydrate, for example in the case of methane [11], or mixed with water ice, for example in the case of carbon dioxide [12]. The efficiency of chemical transport is therefore expected to be mostly controlled by the vigour of thermo-chemical convection.

By employing scaling laws derived from 3D numerical simulations of ice mantle dynamics [10] and phase diagrams constraining from high pressure experiments [11,12], we investigate the possible chemical evolution of planets by exploring a wide range of water content and planet size. We will discuss the impact of icy mantle dynamics on the thermal evolution of the deep interior as well as on the chemical exchanges between the deep silicate interior and the atmosphere.

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