**Production of $H_2$ by radiolysis of water in the cores of icy bodies increases the habitability of the outer solar system**

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**Introduction:** The radiolysis of water produces, among other chemical species, molecular hydrogen [1]. Liquid water surrounded by rocks containing natural abundances of radionuclides can be enriched in $H_2$ by this process. The $H_2$ provides a source of chemical energy that helps to sustain intraterrestrial microbial communities on Earth [2, 3, 4]. Such production of $H_2$ can be envisioned in the rocky cores of icy bodies hosting a liquid water ocean, or even in differentiated bodies that lack an ocean. While serpentinization (the aqueous alteration of ultramafic rocks) is the most often considered source of $H_2$ in such settings (e.g., [5]), it requires continuous exposure of unaltered rocks to water and appropriate temperature conditions. Here, we investigate the potential for $H_2$ production by radiolysis and its relative importance compared to serpentinization.

**Model:** We used a geochemical model of radiolysis developed for Earth sediments [4], which calculates the amount of energy from α and β particles and rays that is deposited into water. The $H_2$ production rate is then computed from published yields (G values; [5]). The model assumes that the energy deposition into water vs. rock depends on the volume ratio and stopping powers of these materials. The radiation comes from long-lived radionuclides $^{40}K$, $^{232}Th$, $^{235}U$, and $^{238}U$, with assumed abundances consistent with measurements of ordinary chondrites [6]. The porosity of the rock (assuming the interstices are all filled with liquid water) plays a determining role in the production rate of $H_2$ (Figure 1).

**Application to icy bodies:** We performed calculations of $H_2$ production for several known or suspected ocean worlds: Europa, Ceres, Titania, Oberon, Pluto, and Charon. We explore the consequences for $H_2$ production in a model where water from the ocean percolates deeper into the core as time passes in response to thermal cracking due to cooling [7,8]. We calculated

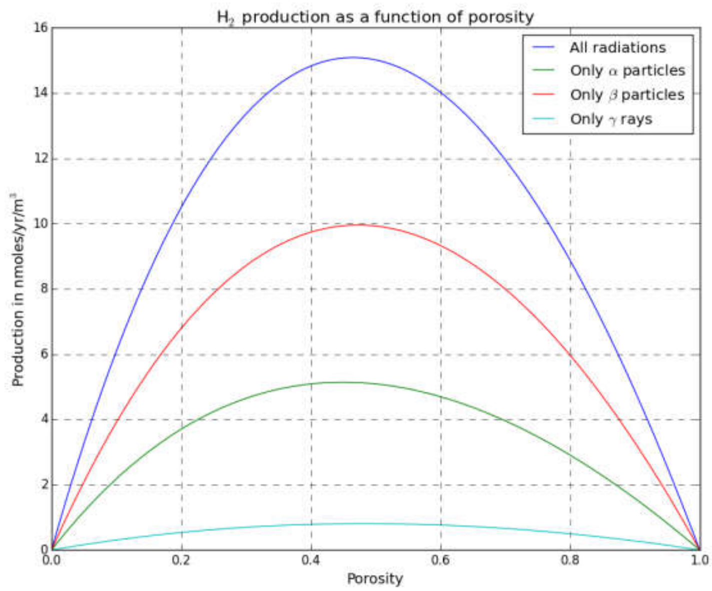


**Figure 1: Present-day production of $H_2$ in 1 $m^3$ of chondritic sediment, depending on porosity.**

the production of $H_2$ by radiolysis in the volume accessible to ocean water and compared it to the published estimates of production from serpentinization [7].

The radiolysis/serpentinization ratio for the cumulated production of $H_2$ is shown in Figure 2. We assumed a porosity of 2.5%, consistent with studies of serpentinite from earthly seafloors [9]. It should be noted that close to the seafloors in small icy worlds, much higher porosities, up to 50%, can be envisioned [10] while the inner core may be compacted by creep to the point of effectively having no porosity [11].

We find the ratios of cumulated productions to range between 5 and 10% today (Figure 2). Despite the water penetrating deeper with time, the exponential depletion of radionuclides ensures the production decreases with time for all bodies considered.

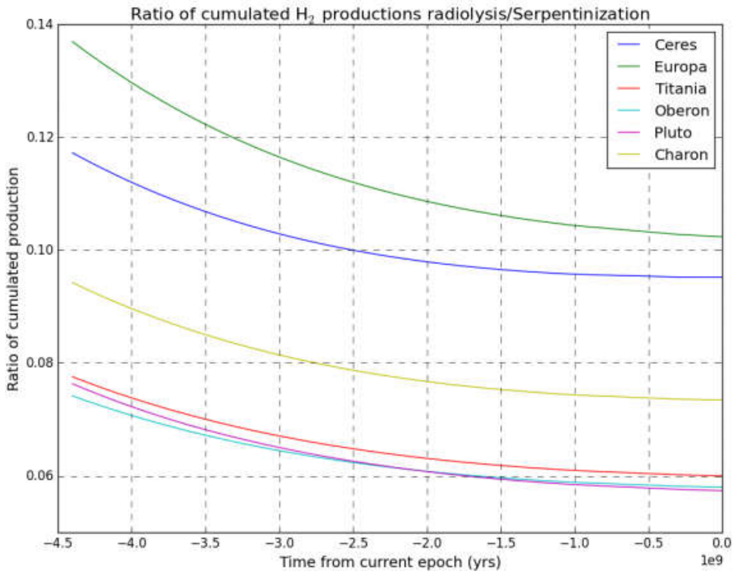


**Figure 2: Evolution with time of the ratios of cumulated productions, with a bulk porosity of 2.5%.**

While not having the potential for high $H_2$ yield of serpentinization, radiolysis nonetheless can provide a non-negligible steady flux of $H_2$ to this day. Figure 1 shows a higher value of porosity can drastically augment the production; for a porosity of 25 %, the ratios seen in Figure 2 would be higher by an order of magnitude; bringing production by radiolysis to the level of serpentinization for Europa and Ceres. Radiolysis allows $H_2$ to be produced inside geophysically inactive icy worlds, which may make them more habitable than currently thought. The sole requirement is the presence of liquid water in contact with rock. Also, radiolysis of water unavoidably produces oxidants [1], opening the possibility for $O_2$ and sulfate production [12], which could serve as electron acceptors for microbial metabolism (methanotrophy, sulfate reduction). If $H_2$ escapes to space and oxidants accumulate in the interior, radiolysis would lead to the net oxidation of ocean worlds, which could have profound effects on the stabilities of redox-sensitive volatile elements, including the synthesis of organic materials. The potential of water radiolysis to support habitability of ocean worlds does not stop at the production of molecular hydrogen.

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