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Clathrate Hydrates in Icy Moons: Experimental and Modeling Studies on the CH_4-CO_2-H_2O and CH_4-NH_3-H_2O Systems

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The hydrosphere of volatile-rich objects in the outer Solar System likely contains clathrate hydrates. These compounds exhibit many physical properties similar to those of water ice I_h. However, differences in mechanical strength, thermal conductivity and density may substantially impact geologic processes, and the stability, composition and distribution of multicomponent clathrates in ocean worlds remain poorly constrained.

This study examines the composition of mixed clathrate hydrates that could form in ocean worlds and assesses their potential to sink or float, contributing to the formation of a clathrate layer at the top or bottom of the internal ocean. Using a model based on the statistical thermodynamic approach of van der Waals and Platteeuw [1], we evaluate the composition and density of mixed clathrate hydrates forming in pure water systems as well as in the presence of ammonia, an important thermodynamic inhibitor likely present in small amounts on icy moons. For the ammonia-bearing systems, we express the activity coefficient of water in the liquid phase based on the Margules equation as proposed by Choukroun and Grasset [2]. Our model is applied under conditions relevant to Europa, Titan, and Enceladus (255 K to 273 K and pressures up to several hundred MPa) and is compared with experimental cage occupancies and selectivity retrieved from Raman spectroscopy of mixed CH_4-CO_2 clathrate hydrates in pure water, and with preliminary high-pressure microcalorimetry dissociation temperature for the CH_4-NH_3-H_2O system.

Given their influence on the thermal and rheological properties of ocean world ice shells, the timing, abundance, and location of clathrate reservoirs should be considered in evolution models. This work provides valuable insights for interior modeling of icy bodies and supports ongoing and future missions, including JUICE, Europa Clipper, and Dragonfly.

[1] J. van der Waals, J. Platteeuw (1958) *Adv. Chem. Phys.*, **2**, 1-57.

[2] Choukroun M. and Grasset O. (2010) *J. Chem. Phys.,* **133***,* 144502.