GEOPHYSICAL IMPLICATIONS OF CARBON CYCLING IN OCEAN WORLDS. J. C. Castillo-Rogez[1], S. W. Courville[1,2], M. Melwani Daswani[1], J. Diab[3], J. M. Weber[1], [1]Jet Propulsion Laboratory, California Institute Technology, Pasadena, CA (julie.c.castillo@jpl.nasa.gov), [2]School of Earth and Space Exploration, Arizona State University, Tempe, AZ. [3]Chemistry and Biochemistry Department, University of California, Los Angeles, CA.

Introduction: Evidence for organic matter (OM) on water-rich bodies has been found throughout the solar system over the past decades, with space missions (Cassini-Huygens, Dawn, New Horizons) and ground-based observations (e.g., asteroids, Kuiper belt objects like Pluto and Triton). In particular, organics have been detected in Enceladus' plume, in Titan's atmosphere, and on dwarf planet Ceres [1,2,3]. Other forms taken by carbon have also been observed (carbonates) or are suspected (gas hydrates) on these bodies [2,3]. Recent solar system dynamical evolution and icy body accretion models suggest cometary material could represent a significant source of carbon compounds (ices, organics) in many outer solar system bodies [4]. A large fraction of organic matter could explain the low densities inferred for the rocky mantles of Titan and Ganymede [5].

Because they could be abundant, carbon compounds can alter the bulk thermophysical properties of mixtures. Hence, the ways carbon ices and organics are partitioned following accretion can have important consequences on the internal evolution of icy moons and dwarf planets. Furthermore, the prospect of tens of wt.% of organics in cometary material [6] would effectively dilutes radioisotope abundances and lead to colder rocky core temperatures than for models assuming a CI chondrite composition. Here, we track possible evolution pathways for carbon compounds and assess their consequences for the thermal evolution of ocean worlds.

Carbon Cycle in Ocean Worlds: We follow the sources and sinks of accreted carbon compounds: ices (like CO_2, CH_4), organic matter (OM), and carbonates if a body accreted from carbonaceous chondrite material. Depending on formation location, the fraction of carbon accreted by icy bodies can vary significantly: from a few wt.% in the formation regions of most carbonaceous chondrite parent bodies, presumably < ~7 au [7] to several tens of wt.%, in the form of OM and carbon ices in the Kuiper belt [8].

Key steps in the evolution of icy bodies that drive the fate of carbon compounds are: (1) volatile-rock interaction that can lead to the formation of carbonates or additional organics [9]; dissolved gas compounds can also form gas hydrates (clathrates); (2) sinking of OM with rock during the separation of a rocky core; (3) maturation of organics trapped in the core and release of CO_2 and short-chain hydrocarbons as a consequence of thermal metamorphism (decarboxylation and organic matter breakdown); (4) fluids released from the core during thermal metamorphism that can alter the redox conditions in the ocean; (5) exposure of carbonates (e.g., evaporites from extruded brines), gas (e.g., cryovolcanism), and OM [3].

Methane clathrates are expected to form readily; on the other hand, carbon dioxide clathrate formation depends on the conditions in the ocean, in particular the pH. The latter is determined by the relative fractions of NH_3 and CO_2 [10] and the effective water to rock ratio (W/R). The latter is a function of the size of the object, which determines the extent of hydrothermal circulation, but is poorly constrained. Figure 1 maps the conditions for clathrates to form in various icy bodies: W/R>~4, [CO_2] >~10 wt.% and [NH_3] <~1.7 wt.% are required for clathrates to form. For comparison, the W/R derived for Enceladus is ~0.8-2.4 [11].

As a result, small icy bodies like the Uranian moons are unlikely grounds for CO_2 clathrate hydrate formation but might form clathrates if they accreted methane ice. Ceres falls in the same category; if a high fraction of clathrates is confirmed in Ceres' shell [12], then it would likely be dominated by methane and imply accretion in the far outer solar system.

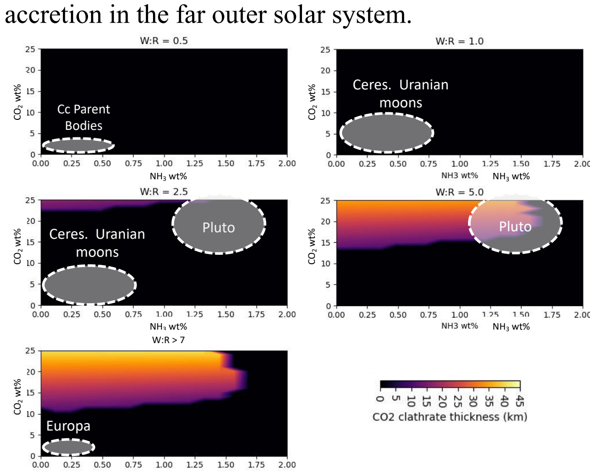

***Figure 1**. Maximum thickness of CO_2 clathrates that may form in bodies across the outer solar system as a function of a rough assessment of the expected accreted wt% of NH_3, CO_2, and the effective water to rock ratio (W:R).*

Implications on Thermal Evolution: First, the relative fraction of refractory carbon determines the amount of accreted radioisotopes. It may be significantly lower (by up to 40%) than for a CI composition. Additionally, clathrates and OM have a thermal conductivity at least one order of magnitude lower than water ice and rock. Clathrates can insulate the hydrosphere from heat loss if low-density (e.g., methane) clathrates accreted at the base of the ice shell. However, they can decrease the heat flowing out of the rocky core if higher density clathrates (e.g., CO_2) sediment at the base of the hydrosphere. In practice, mixed clathrates are most likely to form [13].

OM could be responsible for the relatively low rocky mantle densities inferred from gravity observations for Ceres [14], Ganymede and Titan [5]. For the high fraction of OM assumed by [4], the effective thermal conductivity is decreased by a factor of 2. In the case of a large body, like Titan, a large fraction of OM leads to mantle temperatures below the Fe-FeS eutectic (Figure 2). The difference in carbon content could potentially explain differences between Ganymede and Titan in terms of evolution and extent of differentiation, expressed in a contrast in moment of inertia (0.310 vs. 0.332-0.341, respectively). Lastly, the metamorphism of OM under the high pressure and temperature conditions of large rocky mantles can release a significant fraction of clathrate-forming gases, which represent a potential sink of water [15].

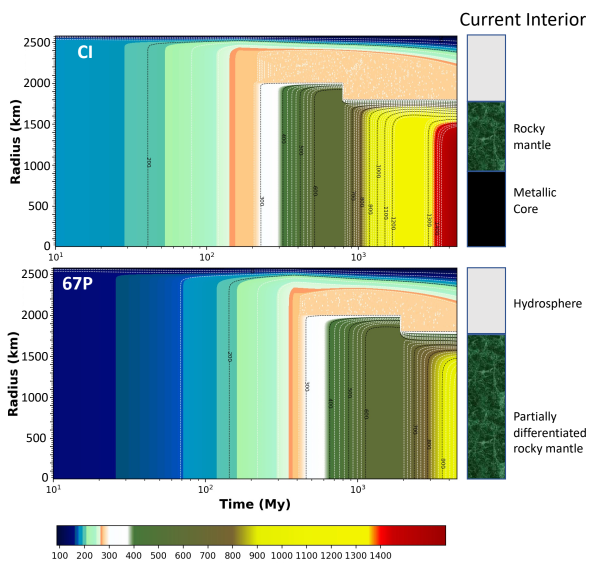

Figure 2. *Thermal evolution models for Titan for a reference time of formation with respect to calcium aluminum inclusions of 4 My (determines the amount of accreted* ^{26}Al*) and different assumptions on the composition of accreted planetesimals: CI vs. cometary, taking 67P as a reference. The latter leads to much colder colder interiors, precluding metallic core formation.*

Summary: A large fraction of accreted OM represents a heat deficit in icy bodies. This needs to be accounted for in models of, e.g., Pluto, Triton, and maybe Titan and Ceres. Furthermore, these models imply a cometary source and thus the co-accretion of carbon ices and ammonia. These may lead to a high salinity due to bi/carbonates and ammonium [10], with potential signatures in the gravity and surface composition. While large fraction of OM can explain the relatively low-density of Titan's rocky mantle [4], a high salinity may also explain the moon's relatively high ocean density [16]. However, estimates of organics abundances up to 45 wt.% are based on observations of comet 67P refractory material and do not necessarily reflect the average composition of planetesimals. Several other caveats and open questions underlie current models – one is the fates of soluble OM vs. insoluble OM; how much of accreted OM sinks with rock, considering the low density of this material at low pressure (~1.3 g/cm^3); the potential migration of low-viscosity OM via diapirism at temperatures of a few 100s °C. More generally, experimental research is needed in order to expand our understanding of OM behavior in icy body settings.

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Acknowledgments: Part of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).