PHYSICAL AND CHEMICAL DIFFERENTIATION OF LARGE ICY ASTEROIDS AS A FUNCTION OF ORIGIN: APPLICATION TO CERES. J. C. Castillo-Rogez[1], Elizabeth A. Frank[2], Kevin J. Walsh[3], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Blvd, Pasadena, CA 91109, julie.castillo@jpl.nasa.gov, [2]Dept. of Geological Sciences, University of Colorado, 2200 Colorado Ave, Boulder, CO 80309, [3]Southwest Research Institute, 1050 Walnut St. Suite 400, Boulder, CO 80302.

Introduction: We address the differentiation of icy dwarf planets with a focus on Ceres in order to plan for observations to be performed by the *Dawn* spacecraft in 2015. We explore the relationship between Ceres' original volatile composition and its accretion timeframe and timescale and combine geophysical and chemical modeling in order to assess how prospective observations with the *Dawn* spacecraft can trace back to constraints on the accretional environment of Ceres.

Origin of Icy Asteroids: Several formation scenarios have been proposed for large volatile-rich asteroids, Ceres in particular:

- In situ in the asteroid main belt (#MBA), within the snowline and volatile composition [1];
- Accretion in the Kuiper Belt (#OSS) and migration to the asteroid belt [2];
- Accretion in the Jupiter/Saturn region and migration through the Grand Tack (based after [3].) (#GTM);

These models imply very different formation conditions, in terms of temperature, accretion timescale, abundance of short-lived radioisotopes, and planetesimal chemistry and history prior to accretion (Table 1).

Modeling Approach: In order to constrain Ceres' chemical evolution, we have coupled physical and chemical modeling. For the first step of this study we have considered the impact of temperature on the chemistry of an early ocean layer. For this we used the commercial software *Geochemist's Workbench* using as input the average elemental composition of carbonaceous chondrites with the addition of ammonia and carbon dioxide. Temperature was varied from 0 to 70°C, matching those inferred from oxygen thermometry of carbonaceous chondrites [4]. Partial pressure was taken at log pH_2 = -2.5 to represent the conditions at the ocean-core interface in early Ceres (PPM redox buffer) and log pH_2 = -6 for planetesimals less than 100 km in radius.

The *Geochemist's Workbench* cannot handle temperatures lower than 0°C, but our results so far show a major decrease in the amount of transfer of major elements from the rock to the liquid phase with decreasing temperature, a phenomenon confirmed by experimental research ([5]). The modeling also accounts for the feedback between chemical evolution and physical properties of the rock and ice, as well as the loss of ^{40}K.

Parameter	#MBA, #GTM	#OSS
Volatile Temperature	100-150 K	40 K
Accretion Timescale	< 5 My	10-100 My
Short-lived Radioisotopes	Drivers of early differentiation	Impact on planetesimals
Volatile Composition	Water, NH_3, clathrates, CO_2	Water, ammonia, methanol, clathrates, organics
Planetesimal Alteration	No, rapid accretion of small planetesimals	Yes, accretion of large, evolved planetesimals

Table 1: Some of the features specific to each accretional environment considered in this study.

Chemical vs. Physical Differentiation: The geophysical evolution of a Ceres-sized, wet asteroid is represented in Figure 1 as a function of origin. It shows that the final geophysical state of Ceres is mostly independent from its origin. In other words, differences between geophysical evolution outcomes cannot be discriminated against on the basis of moment of inertia measurements only. Similarly, geological evolution is likely to bear little signature of origin, as it is primarily driven by surface temperature (e.g., global relaxation) [6].

In fact, the key difference between these models is the extent of chemical differentiation, i.e., redistribution of elements between the rock and an early liquid phase. It scales with temperature and the duration of hydrothermal activity. This chemical redistribution throughout the object also depends on the potential for mass transfer. Previous works demonstrated that objects larger objects are subject to more efficient hydrothermal circulation [7]. The surface may be produced via solid-state convection in the thickened icy shell and/or cryovolcanism. Hence, the surface chemistry record is a gauge of differentiation, but that fingerprint may be only partial depending on filtering imposed by the surface emplacement mechanism. In turn, only those bodies that are large enough for physical differentiation may undergo resurfacing.

Based on these considerations the presence of carbonates at the surface of Ceres [8] point to a phase of intense hydrothermalism and is best explained by a warm early history, as that enabled by model #MBA. Also, in this context, the 3-μm feature in [9] is most logically interpreted as evidence for brucite. As salts are easily transported due to their solubility, they lend themselves to observations. Hence this model is to be further tested by *Dawn* through the search for salt markers of reducing environments.

Conclusion: The key conclusion that Ceres would have acquired most of its volatiles in the main belt or Jupiter-Saturn region is consistent with recent geochemistry measurements of carbonaceous chondrites [10]. Similarities in surface spectral properties for Ceres and Hygeia [11] support this conclusion and point to a common genetic origin for the two bodies. In contrast, the presence of water ice but absence of hydrated minerals at Themis [see 12 for a review] implies a different accretion timeframe consistent with [13]. Extending this study to other asteroids in the class range 300-1000 km, we suggest specific chemical signatures to be sought out by *Dawn* and future missions to these bodies.

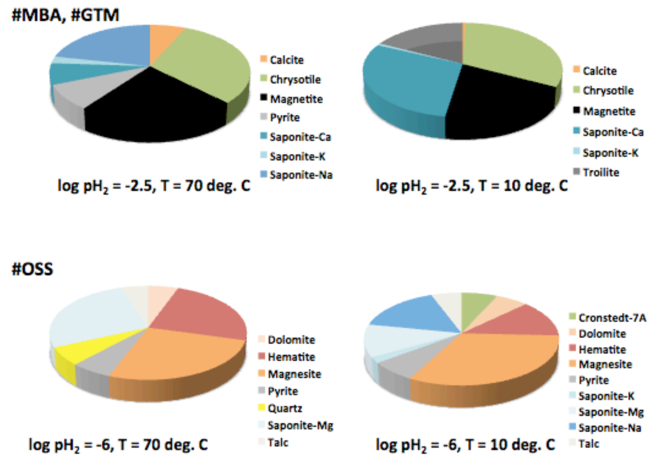

Figure 2. Mineralogical assemblages for the #MBA and #OSS models various models considered in this study.

References: [1] Dodson-Robinson, S. et al. (2009) *Icarus* 200, 672-693; [2] McKinnon, W. (2012) DPS 2012; [3] Walsh, K. et al. (2012) MAPS in press; [4] Keil K. (2000) PSS 48, 887-903; [5] Mironenko, M. and Yolotov, M. (2012) Geoch. Int. 50, 1-7. ; [6] Castillo-Rogez et al. submitted; [7] Young, E., et al. (2003) *EPSL* 213, 249-259; [8] Rivkin, A. S. et al. (2006) *Icarus* 185, 563-567; [9] Milliken, R., Rivkin, A. (2009) *Nat. Geosci.* 2, 258-261 [10] O D'Alexander et al. (2012); [11] Takir D. and Emery J. (2012) *Icarus* 219, 641-645; [12] Rivkin, A. S., this session. [13] Jones, T. et al. (1990) *Icarus* 88, 172-192.

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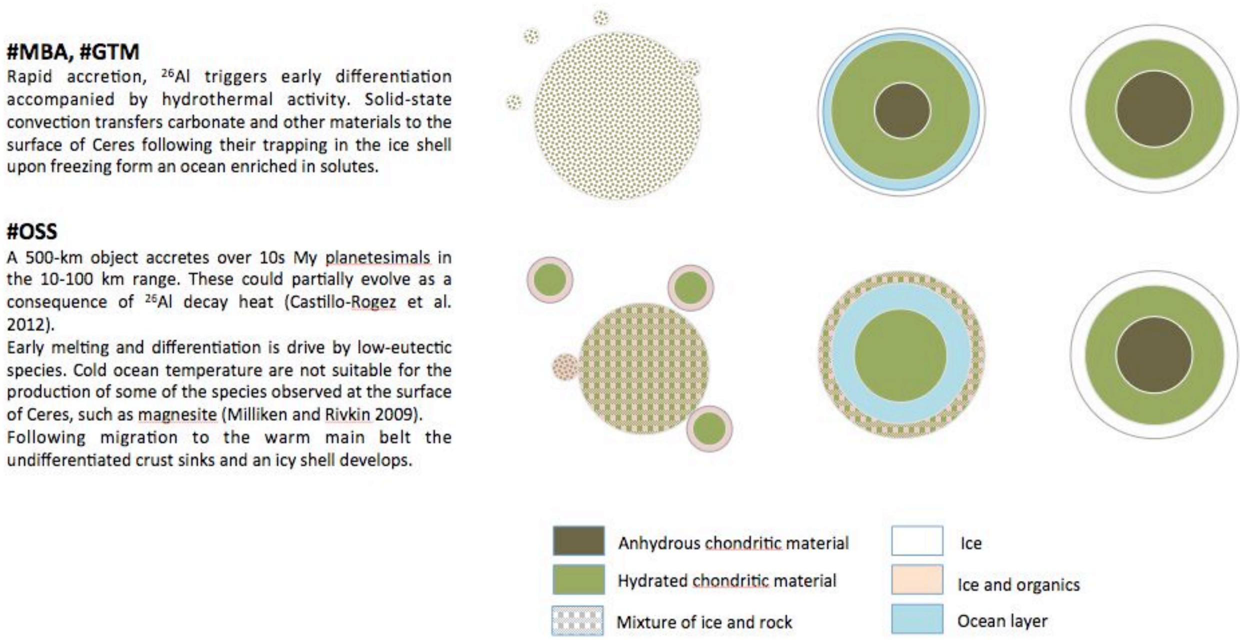

Figure 1. Schematic representation of the accretion and evolution of large wet asteroids for the formation scenarios and assumptions on the origin of their volatiles.