ORIGIN OF CERES' SURFACE AS A PRODUCT OF MOBILE-LID CONVECTION J. C. Castillo-Rogez[1], M. Choukroun[1], R. P. Hodyss[1], P. V. Johnson[1], A. S. Rivkin[2], and C. A. Raymond[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States (jccastil@jpl.nasa.gov), [2]Applied Physics Laboratory, John Hopkins University, Laurel, MD, United States.

Introduction: As the largest main belt asteroid, Ceres is a primary target of exploration. Its abundant content in water makes it a parent to outer planet satellites [1, 2]. However, its warm surface temperature, up to 200 K at the equator, more than 100 K greater than icy satellite surface temperatures, implies that its potential for endogenic activity is different from that observed or modeled for icy satellites. The asteroid differs from other C-class objects as its surface composition (a mixture of brucite and magnesite) is not matched by any available chondrites [3]. The global distribution of that material has been interpreted as the consequence of pervasive hydrothermal alteration of clay-rich material. However, the origin of that assemblage, formed at depth or in the subsurface, is not constrained. Ceres' surface is also outstandingly uniform in comparison to other C-class objects. We demonstrate that all conditions were met for mobile-lid convection to take place in Ceres in the past, and that its peculiar surface is evidence for the occurrence of that mechanism.

Convection in Ceres: Ceres' density indicates that the asteroid contains about 40wt.% water [1, 2]. Shape data suggests that this object is differentiated into a rocky core dominates by hydrated silicates and an outer icy shell a few tens of kilometers thick [2]. Ceres' physical properties are thus similar to Saturn's satellite Dione, which prompted McCord and Sotin [1] to model convective heat transfer in that object after the parametric approach developed for stagnant-lid convection, a regime typical of icy satellites due to their low surface temperatures resulting in a large contrast in viscosity across their icy shells. However, at Ceres, that viscosity contrast is only a few orders of magnitude, due to the warm surface temperature of that object, located only ~2.7 AU from the Sun. In that case, another style of convective heat transfer may act. The style of convective heat transfer is determined by several parameters [4], functions of the thickness and the surface and bottom temperatures of the icy shell (Fig. 1), as well as the heat flow across the surface. The potential for stagnant-lid vs. mobile-lid convection in Ceres evolved with time as long-lived radioisotope decayed, and the surface temperature increased in response to the Sun's increasing luminosity [5]. We found that all requirements were met at some point in Ceres' history, starting about 2.5 Gy ago, for mobile-lid convection to become the most likely heat transfer regime in Ceres.

Surface Material Origin: Magnesite and brucite are the most common products of hydrothermal alteration in presence of carbon dioxide. Magnesites are commonly found next to dolomite in CI chondrites [6]. Brucite is a typical product of the breakdown of forsterite under low-temperature (<300 K) aqueous alteration. These compounds could have formed early in the planetesimals that accreted into Ceres, later on during the melting of Ceres' ice and consequent differentiation [2], or during a later stage as a consequence of cooling cracks developing in Ceres' core.

On Earth mobile-lid convection is associated with magmatic activity, i.e., at mid-oceanic ridges; similarly, we expect convective plumes in Ceres to be accompanied by cryovolcanic activity. We suggest that the materials found on Ceres' surface were involved in passive transport along warm upwellings in the convective ice shell. In this scenario, brucite and magnesite formed during serpentinization of Ceres' silicates would be first solubilized in an early liquid layer, then transported across the icy shell to the surface. We do not know the thickness of the assemblage inferred from IR measurements, except that it does not need to be thicker than a few millimeters in order to be detected. The solubilities of brucite and magnesite in liquid water at standard conditions are 3.7 and 4.2 ppm, respectively [7, 8]. Therefore, only 6×10^6 km^3 of liquid water, i.e. ~ 3-5% of the total volume of available water, are required to solubilize the amounts of brucite and magnesite equivalent to a surface layer thickness of 1 cm. The solidification of the ocean would induce the precipitation of some of the minerals in the growing ice shell, where they would remain trapped as impurities along grain boundaries [9]. At these low temperatures magnesite may precipitate in hydrated form (e.g., nesquehonite or lansfordite) [10]. Brucite and hydrated magnesite would represent no more than a few ppm (in volume) of the solids, so their presence would not alter the mechanical properties of the ice, and they would be easily transported to the surface by convective upwellings. Under the mobile-lid convection regime, material may be supplied to the surface at a velocity of the order of 10^{-7} m/s. At that rate, the entire surface of Ceres could be resurfaced in a few tens My.

Fate of Materials Delivered to the Surface: ice and hydrated minerals may be altered as a consequence of surface chemistry. The surface of Ceres, like other airless bodies in the solar system, is subject to a variety of radiation sources, including solar photons, the solar wind (H+, He++ and electrons), and cosmic ray ions. Of the photons, only UV-C photons (4.4-12.4 eV) and EUV photons (>12.4 eV) [11] have sufficient energy to fuel chemical reactions. Further, comparing flux levels appropriate to Ceres orbit shows that the energy flux of UV-C photons is four orders of magnitude or more greater than that of EUV photons, the solar wind, and cosmic ray ions. As such, UV-C photons represent the most chemically relevant radiation source on Ceres surface. It is likely that the shorter wavelength, higher energy UV available on Ceres would lead to extensive dehydration reactions. In addition to UV-induced dehydration, photons with wavelengths less than about 200 nm (6 eV) can break water into H and OH, both highly reactive species that could subsequently react with and alter the minerals. Detailed compositional mapping that will be provided by the *Dawn* Mission offers the prospect to use the dehydration reactions products as tracers for constraining Ceres' surface age, on top on the crater counting data that will be provided by high-resolution imaging.

Summary: We suggest that Ceres is one of the very few objects, for which mobile-lid convection may be a key mechanism in the transport of heat and material from the interior, with potentially important astrobiological implications. Upcoming observations by the *Dawn* Mission offers the prospect to test this scenario.

References: [1] McCord T. B. and Sotin C. (2005) *JGR,* 110, CiteID E05009. [2] Castillo-Rogez J. C. and McCord T. B. (2010) *Icarus,* 205, 443-459. [3] Milliken R. and Rivkin A. S. (2009) *Nature Geoscience,* 2, 258-261. [4] Barr A. C. (2008) *JGR,* 113, CiteID E07009. [5] Endal A. S. (1980) In: Variations of the Solar Constant, NASA Conference Publication CP-2191, 175–181. [6] Johnson C. A. and Prinz M. (1993) *GCA,* 57, 2843-2852. [7] Hostetler P. B. (1963) *Am. J. Science*, 261, 23-258. [8] Morey G. W. (1962) *Am. Min.*, 47, 1456-1460. [9] Cullen D. and Baker I. (2001). *Micros. Res. Techn.*, 55, 198-207. [10] Coleyshaw E. E. et al. (2003) *Spectrochim.Acta A*, 59, 2231-2239. [11] Madey T. E. et al. (2002) *Surface Science*, 500, 838.
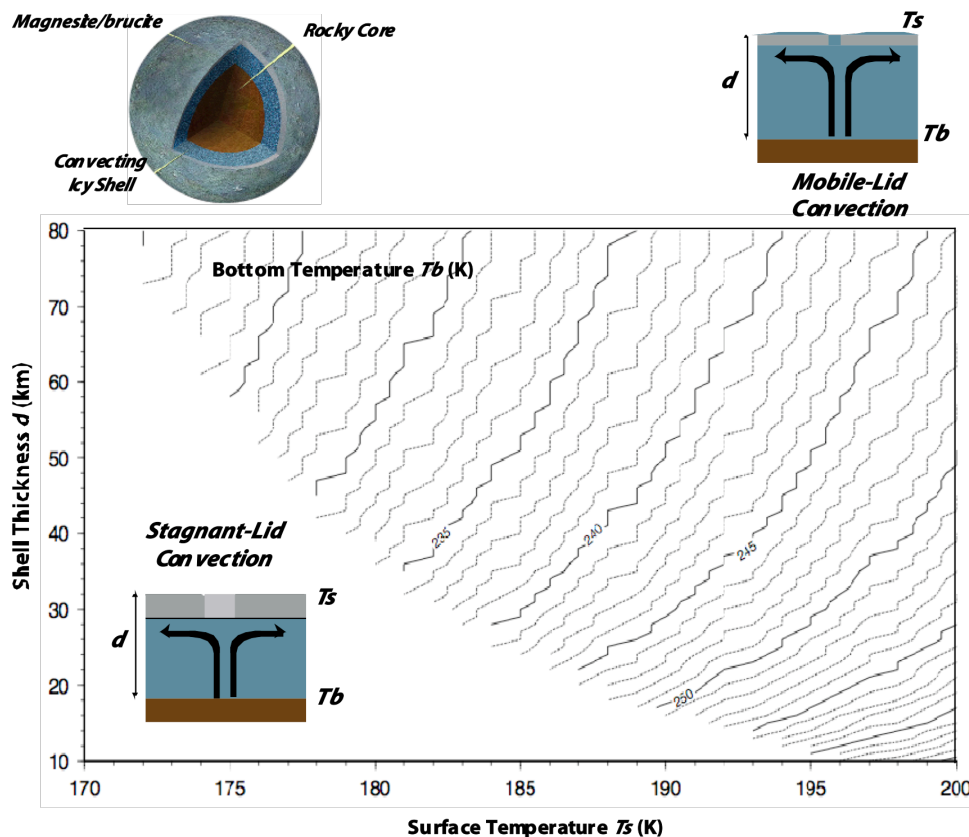
Figure 1. Sets of surface and bottom temperatures, and icy shell thickness for which all the conditions for mobile-lid convection onset are met. The surface temperature is ranged between the expected value at the equator 4.5 Gy ago, and Ceres' current equatorial temperature.