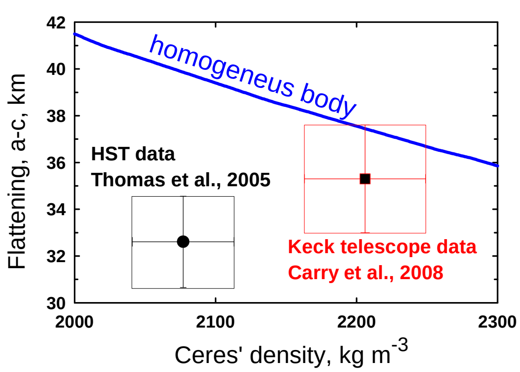
CERES: A CASE FOR POROUS, UNFIFFERENTIATED, AND NON-ICY HYDRATED BODY. M. Yu. Zolotov, School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287-1404; e-mail: zolotov@asu.edu.

Introduction: The dwarf planet Ceres has a diameter of ~950 km, and it is the largest object in the asteroid belt. Ceres has a density of ~2040-2250 kg m^{-3}, and a dark non-icy surface with signs of hydrated minerals [1-5]. The low density implies that Ceres contains a significant fraction of voids and/or low-density compounds. These compounds could be presented by hydrated and OH-bearing minerals (phyllosilicates, salts) and ices [1], as well as clathrate hydrates and organic species. McCord and Sotin [1] considered several models for the internal structure and advocated for a differentiated structure with a nonporous rocky core, a water mantle, and an uppermost rocky layer. As opposed to inferences presented in [1-3], this work argues for a porous rocky internal structure of Ceres that may not have the rocky core and the water mantle.

Deductions from the body's shape: Current astronomical data on Ceres' size, shape, and mass are not certain enough to determine the degree of differentiation. Assuming hydrostatic equilibrium, Hubble Space Telescope (HST) data of Ceres' shape and size imply a differentiated inferior structure [2]. However, Keck telescope observations [3] do not exclude partially differentiated or even undifferentiated interior structure (Fig. 1).

The interior of today's Ceres is not hot [1], and the body is not large enough to insure an attainment of hydrostatic equilibrium. Even for Callisto, hydrostatic equilibrium may have not been attained [6]. The achievement of hydrostatic equilibrium is less favorable if Ceres has no low-viscosity water mantle. An early cessation of interior processes driven by decay of ^{26}Al [1,7], and the only mild warming by long-lived ^{40}K and ^{232}Th [1] could have limited changes in the body's shape throughout history.

Fig. 1. Recent data on Ceres' shape and density. The Y axis shows the difference between equatorial (a) and polar (c) radius. The solid curve represents modeled shape-density relations for a homogeneous body with rotation period of 9.07 hr at hydrostatic equilibrium [2].



The rocky surface as a sign for undifferentiated interior: An existence of a rocky layer atop a water mantle is unfavorable owing to gravitational instability, as demonstrated for icy satellites [e.g. 8,9]. At least a temporal existence of a thick layer of liquid water below a rocky crust makes the overturn likely. Impacts and tectonic movements caused by phase volume changes during differentiation and water-rock reactions (if they occurred on Ceres) could have favored a submergence of the rocky crust.

If a water layer has formed on Ceres, the liquid fraction (an ocean [7]) should have contained solutes leached from rocks and accreted non-water ices. If the upper rock layer sunk into water, subsequent sublimation of an icy envelope would have led to abundant surface salt deposits, which are not observed. If follows that Ceres may not be differentiated.

Insights from porosity of sediments and chondrites: Terrestrial sedimentary rocks preserve significant porosity at pressures of ~140-150 MPa [10,11] that may characterize Ceres' center. Clastic rocks (shale, sands) can have ~3-13% porosity; and sands have higher porosity. If grains are cemented, the porosity could be higher than that in sands. Sandstones are the least compactable sedimentary rocks and may have 5-15% porosity at ~150 MPa [12]. Sandstones are the best analogs of chondritic materials [13] that probably represent Ceres' rocks.

Different classes of chondrites have average porosity of ~10% (except CI and CM carbonaceous chondrites with porosity > ~20%) [13]. Porosity of chondrites is not a function of metamorphic grade and shock state. In most chondrite types (except probably CI and CM), impact-generated microcracks are mainly accountable for the total porosity [e.g. 13]. The large contribution of microcrack porosity in chondrites may account for the limited compressibility of their parent

Table 1. Ceres' porosity evaluated from grain densities of CI and CM carbonaceous chondrites.

	Average grain density, kg m^{-3}	Average calculated porosity, %
CM chondrites[a]	2900 ± 80	23.1 ± 4.7
CI chondrites[a]	2460 ± 40	35
Ceres with bulk density of 2077 ± 36 kg m^{-3} [2]		
CM material	2900 ± 80	28.4 ± 0.8
CI material	2460 ± 40	15.6 ± 0.3
Ceres with bulk density of 2206 ± 43 kg m^{-3} [3]		
CM material	2900 ± 80	23.9 ± 0.7
CI material	2460 ± 40	10.3 ± 0.2

[a]Data for CM and CI chondrites are from [6].

asteroids [13] and Ceres. If Ceres has the porosity of typical chondrites, there is no need for abundant water phases to be present to account for its low density.

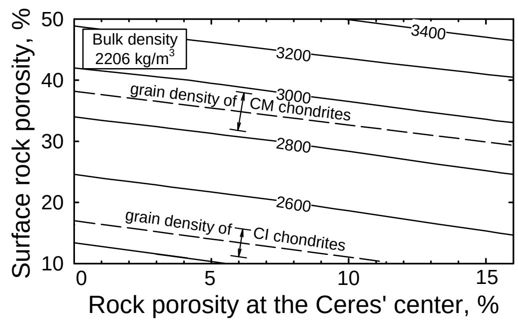
Grain density of Ceres' rocks: If Ceres' rocks have ~10-15% porosity, their grain density corresponds to that of pervasively hydrated CI carbonaceous chondrites (Table 1). It follows that Ceres may consist of a compacted CI-type chondritic material. However, porosity of >20% is needed to account for ice-free rocks with the grain density of CM chondrites. No compaction of the CM material is needed to satisfy the data. If the CM-type material is compacted and has porosity <~22-24%, some water ice or other low-density phases may be present in Ceres' interior. Table 1 shows that Keck telescope data [3] correspond to lesser porosities and are more consistent with a rocky non-icy interior than HST observations [2].

Fig. 2 shows the calculated grain density of porous rocks that satisfy Ceres' bulk density from [3]. In these calculations, porosity changes linearly with pressure, as observed in Earth's sandstones above the depth of ~4 km (at pressure <~100 MPa) [10]. The use of bulk Ceres' density from [2] leads to higher porosities (see Table 1). These results show that Ceres may consist of moderately compacted CI carbonaceous chondritic materials and/or incompacted CM chondritic rocks. The CI-type material is a better analog because it requires less porosity compared to the CM-type material.

An organic-rich body? In addition to hydrated and oxidized phases abundant in CI/CM chondrites, Ceres can be rich in organic matter that contributes to the low density. Ceres' near-infrared reflectance spectra at ~2.3 μm may indicate an elevated abundance of aromatic organic compounds [5]. It is also possible that Ceres is a captured Kuiper Belt Object (KBO) [14]. The KBOs would represent the solar composition and are rich in organic matter compared to chondrites. This notion is consistent with the data on cometary (comet Halley) dust that is rich in "CHON" particles [15]. Even a moderate addition of organic matter to nonporous hydrated rocks with the grain density of CI chondrites leads to values reported for Ceres' bulk density. If Ceres is rich in organic matter, no ice may be needed to account for the body's bulk density. Note that the addition of organic matter is not required to explain the data in terms of hydrated, porous, and non-icy interior structure.

On the formation of Ceres: The Ceres' surface material could represent hydrated planetesimals from which the planet accreted. Ceres could have formed from pervasively altered low-density carbonaceous planetesimals in which ^{26}Al had largely decayed. Abundant water ice may not have accreted. After the accretion, limited heat sources could not caused mineral dehydration and major density stratification.

Fig. 2. The grain density of homogeneous solids distributed according to a porosity gradient in the interior of Ceres for the bulk density of 2206 kg/m^3 from [3].



Conclusions: (1) Current data on shape and density of Ceres are uncertain and do not exclude an undifferentiated interior structure. (2) The observed rocky surface may be inconsistent with a large-scale water-rock differentiation of Ceres. (3) Compressibility data on terrestrial sedimentary rocks together with chondritic data imply that Ceres may have ~5-15% porosity. (4) A compaction-related density gradient in the rocky non-icy interior may account for Ceres' shape and the moment of inertia. (5) Ceres may consist of a moderately compacted CI-type chondritic material without abundant water ice. Non-compacted CM-type chondrites are less likely, but also possible analog materials. (6) If present in the interior, a high organic content could contribute to the low density of Ceres. A high organic content is likely if Ceres is a captured KBO body. (7) Ceres could have formed from pervasively hydrated low-density carbonaceous planetesimals (asteroids) in which ^{26}Al had largely decayed.

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