CERES' SHAPE AGREES WITH AN ORGANIC-RICH INTERIOR STRUCTURE. M. Yu. Zolotov, School of Earth and Space Exploration, Arizona State University, Tempe, Arizona 85287-1404, e-mail: zolotov@asu.edu.

Introduction: Ceres' gravity [1] is interpreted in terms of two-layer interior structures with a hydrated rocky core and a low-density upper layer enriched in ice, hydrated salts and/or clathrate hydrates through a partial differentiation of the body [1-3]. In contrast, Ceres' polar flattening [1] suggests a lesser mass concentration toward the center [2,4,5] and is consistent with compaction of hydrated carbonaceous chondritic rocks without a separation of low-density phases [5]. Data obtained with the Dawn GRaND instrument indicate more than CI-chondritic abundance of C in Ceres' surface materials [6,7]. The elevated C content agrees with abundant surface carbonates [8-10] and opaque amorphous [10] and/or graphitized [11] carbon. Mixtures of CI carbonaceous chondrites with chondritic solvent insoluble organic matter (IOM) and Ca/Mg carbonates provide decent fits for concentrations of C, Fe and H in surface materials [7,10].

Here we model the interior structure of Ceres consisted of rock-organic mixtures to constrain grain density of end member rocks and the mixtures, porosity, upper layer viscosity and composition of the body.

Models: We assume that Ceres' C-rich surface represents the whole body and model the interior composition and density by rock-IOM mixtures. The rock is represented by the composition [12,13, etc.] and grain density [14] of CI (2420 ± 60 kg m^{-3}) and CM (2960 ± 40 kg m^{-3}) chondrites. The used IOM composition $C_{100}H_{70}O_{20}N_{3.5}S_3$ denotes a mildly altered material in chondrites [15]. Density of IOM (1300 ± 100 kg m^{-3}) corresponds to terrestrial analogs [e.g. 16]. The composition and grain density of rock-IOM mixtures are constrained by surface abundances of C, Fe and H [6,7] together with grain densities of the end members. A difference between Ceres' bulk density, 2162 ± 8 kg m^{-3} [1], and calculated density of rock-IOM mixtures is attributed to porosity.

Density distribution in the interior is modeled for the chemically uniform body at hydrostatic equilibrium and is constrained by Dawn data on Ceres' geometric mean radius, mass and rotation period [1]. Density profiles are attributed to either two-layer or gradual compaction models [5,16]. Density and porosity profiles are assessed by solving hydrostatic equilibrium equations for either polar flattening or gravity.

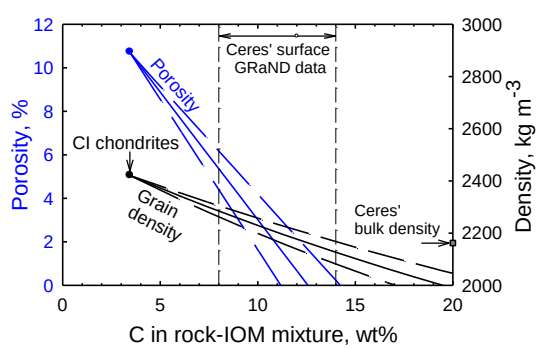
Asphalt cement and bitumen analogs of Ceres' organic-rich materials are used to assess temperature-dependent viscosity of the upper (~120 km) interior.

Results and Discussion: CI-IOM mixtures that agree with the surface C content [6,7] constrain the composition of Ceres' surface and interior. An addition of IOM to the rock dilutes rock-forming and trace elements and increases contents of H and N. Concentrations of Fe and H in modeled mixtures agree with the composition of equatorial areas [6,7]. The consistency of C-Fe-H data in CI-IOM models implies abundant C-H surface materials and agrees with [7,10]. The composition and density of CM-IOM mixtures disagree with surface Fe/H contents and Ceres' bulk density.

In CI-IOM mixtures, C content of 8–14 wt.% [6,7] corresponds to 6.9–16 wt.% IOM and 12–26 vol.% IOM. A nominal value of 12 wt.% C relates to 13 wt.% IOM, 20.5–24.1 vol.% IOM and <2.2 % porosity. CI-IOM mixtures with >11 wt.% C could be inconsistent with Ceres' data because grain density of the mixtures could be less than the body's bulk density (Fig. 1). CI-IOM mixtures with an elevated grain density of the rock end member (~2400–2700 kg m^{-3}) provide a better fit for Ceres' bulk density (Fig. 2). As an example, rock grain density of 2563 kg m^{-3} corresponds to 3.2–6.5 % bulk Ceres' porosity that is similar to that of least porous chondrites [14]. The assessed grain density between that of CI and CM chondrites could reflect the lack or deficiency of hydrated Mg/Na sulfates in Ceres' rocks with bulk composition of CI chondrites.

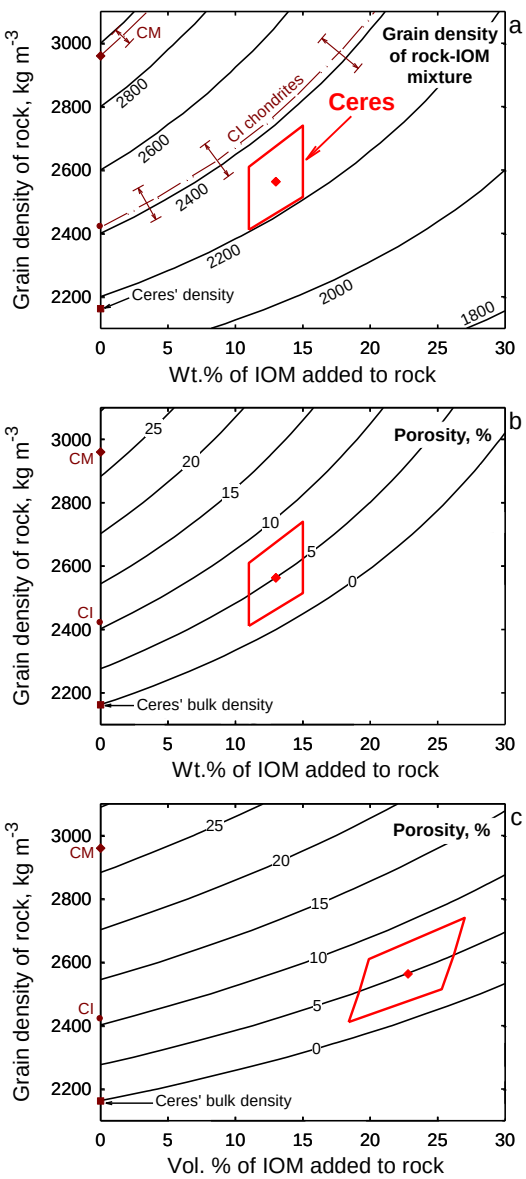
Ceres' shape is consistent with two-layer and gradual compaction patterns of chemically uniform, ice-free and low-porosity materials [5, this work]. At 1.8–6 % bulk porosity, grain density of ~2200–2300 kg m^{-3} (Fig. 3) agrees with that of organic-rich interior implied from the C-rich surface composition (Figs. 1, 2). In contrast, gravity data [1] may not reflect the global density distribution [cf. 4] because the implied bulk porosity >9 % and bulk grain density >2380 kg m^{-3} [5, this work] disagree with organic-rich compositions.

Fig. 1. Grain density and bulk porosity of Ceres consisted of CI chondrite-IOM mixtures as a function of C wt.% in the mixture. Solid curves correspond to IOM density of 1300 kg m^{-3}. Short-gashed and long-hashed curves are for IOM density of 1200 kg m^{-3} and 1400 kg m^{-3}, respectively.



The relaxation of Ceres' topography at long wavelength [3] is consistent with decreasing viscosity of analog rock-organic mixtures (e.g. asphalt cements) with increasing temperature at depth.

Fig. 2. Properties of Ceres consisted of rock-IOM mixtures. The rock has the bulk composition CI chondrites and a variable grain density. IOM grain density is 1300 kg m^{-3}. The large rhombuses show the parameter space at 2–8 % bulk porosity, 11–15 wt.% IOM, 18.4–27 vol.% IOM and rock grain density of 2411–2740 kg m^{-3}. The diamond symbols stand for the mixture characterized by 12 wt.% C, grain density of 2276 kg m^{-3}, rock grain density of 2563 kg m^{-3}, 5 % porosity, 13 wt.% IOM and 22.8 vol.% IOM. Symbols on the Y axis show average grain densities of chondrites [14].



An organic-rich interior implies Ceres' formation at greater radial distances and later than CI chondrites without abundant ^{26}Al. Low K, U and Th contents in modeled CI-IOM mixtures agree with mild density gradients in shape-consistent interior structures.

Summary: Ceres' density and composition is modeled by a low-porosity mixture of chondritic IOM with rocks compositionally similar to CI chondrites with slightly elevated grain density. Density of CI chondrite-IOM mixtures is consistent with density of Ceres' materials in interior structures that agree with the body's shape. The topography is consistent with viscosity of rock-organic mixtures at crustal temperatures. Water ice is not needed to explain an organic-rich Ceres.

References: [1] Park R. S. et al. (2016) *Nature*, *537*, 515–517. [2] Ermakov A. I. et al. (2017) *JGR-P*, *122*, 2267–2293. [3] Fu R. R. et al. (2017) *EPSL*, *476*, 153–164. [4] Mao X., McKinnon W. B. (2018) *Icarus*, *299*, 430–442. [5] Zolotov M. Yu. (2018) *LPS* 49, Abstract #1341. [6] Prettyman T. H. et al. (2017) *Science*, *355*, 55–59. [7] Prettyman T. H. et al. (2019) *Icarus*, *318*, 42–55. [8] De Sanctis M. C. et al. (2015) *Nature*, *528*, 241–244. [9] Carrozzo F. G. et al. (2018) *Science Adv.*, *4*, e1701645. [10] Marchi S. et al. (2018) *Nature Astron.*, doi:10.1038/s41550-018-0656-0. [11] Hendrix A. R. et al. (2016) *Geophys. Res. Lett.*, *43*, 8920–8927. [12] Palme H., et al. (2014) *Treatise on Geochemistry* 2nd Edit., vol. 2, 15–36. [13] Lodders K., Fegley B., Jr. (1998) *The Planetary Scientist's Companion*. Oxford Univ. Press. [14] Flynn G. J. et al. (2018) *Chemie der Erde*, *78*, 269–298. [15] Alexander C.M.O'D. et al. (2017) *Chemie der Erde*, *77*, 227–256. [16] Zolotov M. Yu. (2009) *Icarus*, *204*, 183–193.

Fig. 3. Parameters of two-layer isochemical interior structures consistent with Ceres' shape. Zero core porosity sets lower limits for grain density (~2200 kg m^{-3}) and bulk porosity (~1.8 %). The rhombus shows conditions limited by the upper layer thickness of 38–45 km [2] and core porosity of 0–5 %. The diamond stands for the structure with the upper layer thickness of 41 km and 5 % bulk porosity.