INTERNAL STRUCTURES OF CERES AND ENCELADUS: COMPARISONS AND CONTRASTS.
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Introduction: The dwarf planet Ceres and the "dwarf moon" Enceladus are a study in contrasts, but also offer potentially informative points of comparison. Second-degree gravity measurements for both bodies imply degrees of differentiation [1-4], but the shapes of both are consistent with less separation of ice from rock [2-6]. In Enceladus' case, evidence for strong tidal heating, and a subsurface ocean or regional sea, naturally led to the hypothesis of an isostatic, floating ice shell as an explanation for that moon's excess topography [3]. In Ceres' case it is not clear that a similar explanation is plausible given Ceres' modest radiogenic heat output and limited equatorial crater relaxation [7,8]. For Enceladus, evidence for forced libration of its ice shell not only "proves" the existence of a global ocean [9], but implies a global shell much thinner (~25 km) than that nominally consistent with gravity modeling [4]. Here we examine both issues.

Ceres: The Dawn Mission has vastly improved the accuracy of Ceres' shape and mass [1,2]. Despite the observation of slight triaxial shape [±1 km [10]], we model Ceres as an oblate spheroid because of its rapid spin rate. Using parameters from [1,10] (see Table 1), we followed the second-order recursive method of Tricarico [11] and constructed two-layer models of Ceres in hydrostatic equilibrium. This method assumes ellipsoidal level surfaces, and is sufficiently accurate for our purposes – which are primarily illustrative. We examined outer shell densities from 920 kg m^{-3} to 2000 kg m^{-3}. We also looked at Ceres shapes whose polar and equatorial radii were increased or decreased by ~1σ in a manner to give slightly greater or lesser flattenings, while preserving the mean density.

Figure 1 shows our solutions, which nominally imply average shell thicknesses between about 20-to-135 km. From this result, we favor a differentiated Ceres rather than a homogeneous one (as has already been

Parameters	Value
GM	62.6315 ± 0.001 km^3 s^{-2}
Spin Period	952.1532 deg day^{-1}
Equatorial Radius (*a*)	481.6 ± 0.7 km
Polar Radius (*c*)	445.6 ± 1.0 km
Bulk Density [1]	2167.7 ± 8.0 kg m^{-3}

Table 1. Parameters used as input values in our model. [1]Bulk density is calculated from mass and volume, and is slightly different from that in [1].

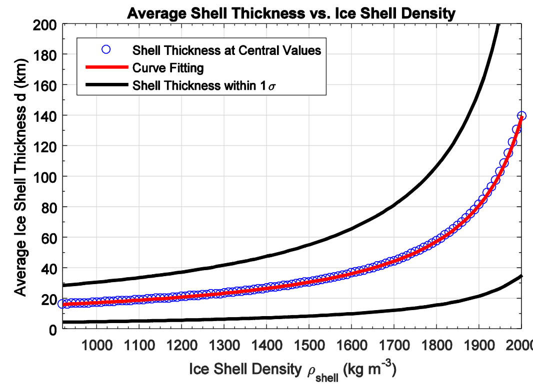

Figure 1. Average shell thickness as a function of shell density. Thick line indicates solutions at observed central values of Ceres' equatorial and polar radius [10]. Thin lines are for (+1/√2,-1) and (-1/√2,+1) km in *a*,*c*.

determined by the Dawn team [1,2]), although within the limits of the observed flattening very little differentiation may be required, but again, provided the figure is hydrostatic. Despite many pre-encounter models with major ice-rich surface layers, Dawn images tell the opposite story: Ceres' outer layers appear rich in dark silicates and possibly salts and carbonates [12], with little obvious evidence for a discrete transition to a rocky interior. Larger equatorial craters *are* substantially more relaxed than polar ones, fulfilling the qualitative, but not the quantitative, prediction of [7], so water ice is almost certainly a component of the outer "shell," however this is defined. Smooth, apparently easily mobilized ejecta deposits are consistent with mud-like

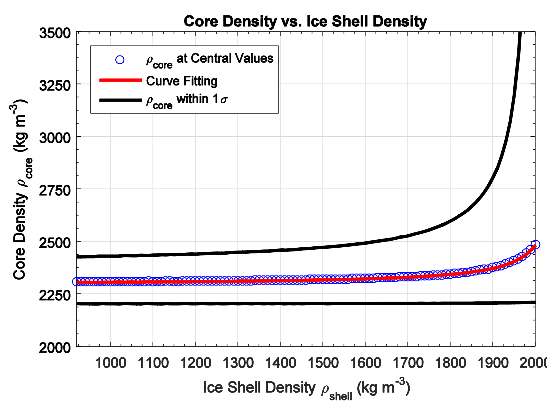

Figure 2. Core density as a function of shell density. Central thick and bounding thin lines are as in Fig. 1.

rheologies, which may owe to impact melting of ground ice (as on Mars).

These inferences from remote sensing imply a Ceres whose outer layer is relatively dense, but still contains enough ice to be rheologically important. The corresponding core densities (for a 2-layer model) are illuminating (Fig. 2). Values start near 2300 kg m^{-3}, increasing slowly with shell thickness, consistent with the bulk densities of carbonaceous meteorites (the least dense class), CMs in particular [13]. Meteoritic bulk densities include porosity, and we expect porosity in Ceres' core to be filled with ice or water, depending on temperature. Hence relatively denser cores in Fig. 2 are favored. It is notable that Enceladus' core is inferred to be relatively low density (2400–2500 kg m^{-3}; [3,4]), and is presumably porous and saturated.

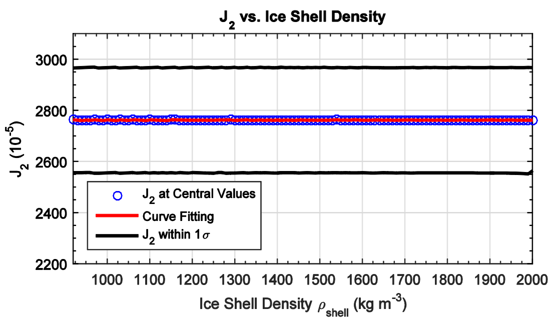

Figure 3. Zonal degree-2 gravity (J_2) as a function of shell density. The J_2 value is consistent over the entire range of shell density, as it must be if Ceres' shape is hydrostatic. Thick and thin lines are as in Fig. 1.

The J_2 inferred from the hydrostatic shape models (~2.76×10^{-2}; Fig. 3), though less than that for a homogeneous Ceres ($\approx 2.88\times10^{-2}$), is greater than the value measured by Dawn, $(2.583 \pm 0.005) \times10^{-2}$ [1]. Thus Ceres' oblate shape is itself, in the end, not hydrostatic. It may be isostatic, possessing a thicker equatorial shell compensated at depth by denser, more rock-rich material, but why the outer shell would possess the necessary degree-2 thickness variation is obscure. The uncertainty in the shape-based J_2 determination (Fig. 3) also allows agreement (barely) between Ceres' shape and its measured J_2, if Ceres is just slightly less oblate than nominal. In this case, the outer shell is relatively thicker, and the core relatively denser (and satisfactorily so) for a given shell density.

Ceres' dynamic topography can be calculated from $a/c = 1 + [1/2 + (a/c)^3]J_2 + a^3\omega^2/2GM$, where ω is the rotation rate. The difference between the dynamic and actual topography (the topographic excess) is slight, only ~1 km. This suggests alternative explanations for reconciling Ceres' degree-2 shape and gravity. One is simply non-hydrostatic effects, given Ceres' level of triaxiality (in both shape and gravity [1,2]). The other is that ω has changed. If Ceres were spinning ≈3.5% faster in the past, its J_2 (determined by its internal structure) and this more rapid spin would be consistent with Ceres present oblateness. Given Ceres' long history of bombardment, it does not seem implausible that Ceres' spin rate, obliquity, and even total mass have changed.

Enceladus: Can the globally averaged, floating ice shell thickness on Enceladus really be only ~20–25 km (Fig. 4 in [9])? Beyond the challenge to Enceladus' tidal energy budget, there is the question of shell properties in the libration model employed. If thicker, rigid shells do not yield a sufficiently large libration, could less elastic rigidity make a thicker shell mimic a thinner one? Along Enceladus' equator, isostatic *lm* = 22 topography should thicken the ice shell by several km at the sub- and anti-Saturn points, and thin it by the same amount at the leading and trailing points of motion [4]. This shell thickness variation (presumably due spatially variable tidal heating), plus any degree-2, longitudinal non-hydrostatic core topography [6], will increase the torque driving the physical libration, again implying a thicker ice shell.

Libration models are beyond the scope of this abstract. Gravity models can be refined, however, to take into account Enceladus' updated triaxial shape [9], and more importantly, the finite amplitude of basal shell topography [e.g., 14]. There is also the question of compensation depth of the ice shell. Different formalisms for spherical shells exist in the literature (e.g., [15] vs. [16]). The latter in particular posits less basal topography, requiring a lower compensation depth (less attenuation), and thus a thinner ice shell, to get the same gravitational effect.

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