AN ICE SHELL ON CERES

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Introduction: Knowing the crustal composition of planetary bodies is profoundly important for understanding global processes like habitability, planetary differentiation, and thermal evolution. Ceres is particularly enlightening in this regard because of its transitional nature, with size between asteroids and planets and location at the boundary of the inner and outer Solar System.

The composition of Ceres' 40-km-thick crust [1] remains debated despite the wealth of data collected by NASA's Dawn mission. Gravity inversions yield a crustal density of 1287^{+70}_{-87} kg/m^3 [1, 2], consistent with a dominant fraction of icy materials, and many geomorphological features have been argued to be indicative of icy material [3, 4], although both sets of observations may be able to be interpreted in other ways [5, 6]. Perhaps most persuasive of an icy crustal content are that large, fresh crater depths match nearly exactly with those of icy moons [7] and that neutron spectroscopy has inferred H_2O [8] consistent with a thermally controlled global subsurface ice table [9] – but the quantitative implications of both attributes for ice content throughout the entire crust are debated.

Despite this evidence, the most common interpretation has been that Ceres' crust only contains a minor fraction (<25–40%) of ice. This conclusion is sourced from analyses of Ceres topography. Previous authors [10–12] have argued that if Ceres' crust was predominantly composed of ice, its topography (especially craters) would have viscously relaxed away to a far greater degree than observed. Instead, they have argued that ice is mixed with >60% of clathrate hydrates, organic matter, salts, and/or silicates, in order to have a mechanically strong crust while also matching the relatively low density constraint.

An icy interpretation: Here, we argue that Dawn data is consistent with Ceres' crust having a higher ice content than previously thought. Rather than invoking a majority of clathrates or organic matter to make the crust light-but-strong, we show that ice on Ceres is stronger (i.e., more resistant to viscous relaxation) than previously calculated.

Our new interpretation is largely motivated by recent laboratory work that has shown a minor constituent of non-icy material may cause major inhibition of ice flow [13]. Typically, models of ice flow on other planets consider multiple deformation mechanisms [14]: the most important for Ceres topography are dislocation creep and grain boundary sliding (GBS). At the temperatures and stresses relevant here, GBS is dominant for *pure* ice (Fig. 1). However, the new experiments of [13] have shown that GBS can be completely impeded if there is a non-ice volume fraction of >6%. For ice fractions below 94%, material deforms much less effectively than previously thought. These authors [13] noted potential implications for Ceres.

Previous viscous relaxation models have proven valuable and used the most advanced ice rheology known at that time, but the new laboratory experiments, as well as some updated thermal calculations that predict colder temperatures [9, 15, 16] compared to some early viscous relaxation models [10], demand that our thinking on the ice content of Ceres' crust be revisited.

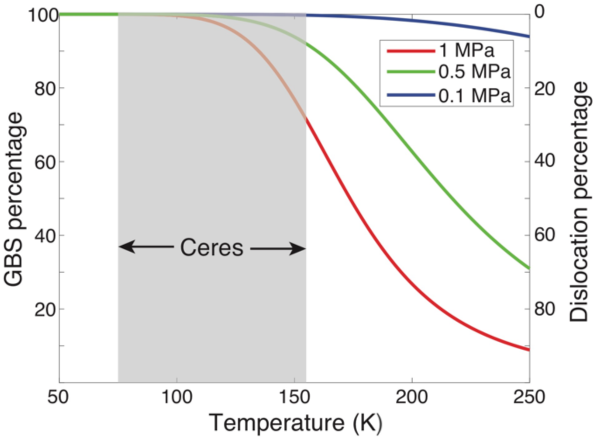

Figure 1. The relative contributions of two deformation mechanisms, dislocation creep and GBS, to strain rate in pure ice of grain size 1 mm. Plotted for 3 relevant shear stresses on Ceres. Note the dominance of GBS at Ceres surface temperatures.

Numerical models: We used the finite element method (FEM) software COMSOL to predict rates of viscous relaxation of craters on Ceres. Our models are 2D axisymmetric and solve the Stokes equations (conservation of momentum and mass). We use a variable-sized mesh, set gravitational acceleration at 0.27 m/s^2, and consider the surface to be a free-boundary condition. We consider simple, parabolic craters with depth/diameter ratios of 0.2. The domain is extended to 4 crater diameters horizontally and 6 crater depths vertically to ensure boundary effects do not significantly bias the calculations.

For our nominal cases, we consider a composition of 80% ice and 20% silicates, which at respective densities of 934 kg/m^3 and 2500 kg/m^3 match the density constraint derived from gravity [2]. This silicate content, if in the form of intergranular particles, inhibits GBS entirely [13] and impedes dislocation creep exponentially [17]. We consider a range of material temperatures from 70–155 K, which are the current annual average temperatures over all latitudes on Ceres [16].

An example result is shown in Figure 2. In this case, a 4-km-diameter crater deforms at a temperature of 145 K (equivalent to a latitude of ~45º). The material has an "effective viscosity" of $\sim 8 \times 10^{22}$ Pa s. The crater deforms into a shallower shape over time, but with maximum viscous flow rate of only 3×10^{-8} m/yr. This flow rate decreases substantially over time as the crater relaxes, and after 300 Myr the crater has shallowed by only 1%. Smaller craters relax at even slower rates, as do higher latitude craters. A similarly sized crater at Ceres' equator relaxes faster, but still not quickly enough to be erased from view on Gyr timescales (maximum flow rate at the onset of relaxation of <1 m/Myr). Decreasing ice content to 50% ice increases effective viscosity by 1 order of magnitude with respect to the nominal 80% ice case.

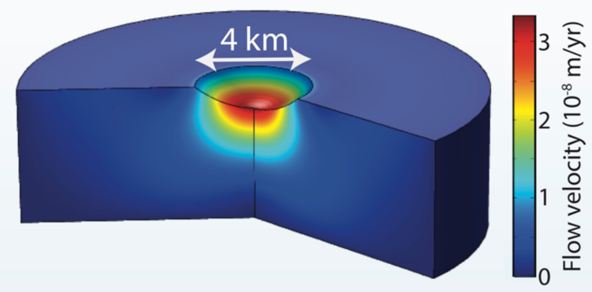

Figure 2. Instantaneous flow velocities for a 4-km-diameter crater on Ceres at 45º if the crust is 80% ice, 20% rock.

Discussion: Our FEM models predict that simple craters on Ceres do not substantially viscously relax over geological time if the crust is composed of 80% ice and 20% rock. Hence, the fact that Ceres contains many craters at the kms-to-10s of km scales should not be interpreted as evidence that the crust is not predominantly icy.

Useful constraints on crustal structure can be derived from consideration of large basins, as was done by [11]. Updating this analysis with the new rheological laws of [13] is the subject of our ongoing work, and we speculate that some non-negligible level of viscous relaxation for these large structures will be estimated. We note that there is evidence that certain specific basins are relaxed [11], that there are fewer large basins on Ceres than expected [18], and that overall crater density of craters with diameter >20 km is lowest at the relatively warm equator [7], all consistent with some degree of viscous relaxation. [12].

If Ceres' crust is 80% ice, many important implications about planetary-scale structure or processes follow. Such an "ice shell" would imply that Ceres is more differentiated than previously thought, as other calculations argue for a total ice plus clathrate component of ~50% [12]. This crustal composition could also make Ceres more similar in geophysical structure to icy moons like Europa in the outer Solar System than currently considered.

Finally, we note that the simulations presented here do not necessarily disprove the currently held notion that Ceres' crust is dominated by clathrates. Furthermore, intermediate ice contents below the 80% ice considered here are allowable (80% ice is likely an upper limit, in order to not violate the crustal density constraint). Ultimately, estimates of crustal strength do not uniquely map to composition. Viscous relaxation or the lack thereof on the solid worlds of the outer solar system may be more indicative of heat flux [e.g., 19, 20] than of composition. Our simulations may thus be used to put constraints on Ceres' geothermal heat flow.

Conclusions: The existence of cratered topography on Ceres does not preclude an icy crust, as ice on Ceres can be stronger than previously calculated. A wide range of ice contents might fit Dawn's observational data, possibly including the case of an "ice shell" that is up to 80% ice by volume. Future spacecraft missions to Ceres will be needed to determine the crustal composition and elucidate the implications about planetary processes that follow. A joint orbiter-lander mission [21] could address this issue.

References: [1] Ermakov et al. (2017), *JGR Planets* 122. [2] Park et al. (2020), *Nature Astro.*, in press. [3] Buczkowski et al. (2016), *Science* 353. [4] Sizemore et al. (2019), *JGR Planets* 124. [5] Zolotov (2020), *Icarus* 335. [6] Johnson et al. (2018), *LPSC* 49th. [7] Hiesinger et al. (2016), *Science* 353. [8] Prettyman et al. (2017), *Science* 355. [9] Landis et al. (2017), *JGR Planets* 122. [10] Bland (2013), *Icarus* 226. [11] Bland et al. (2016), *Nature Geosci.* 9. [12] Fu et al. (2017), *EPSL* 476. [13] Qi et al. (2018), *GRL* 45. [14] Durham and Stern (2001), *Annu. Rev. Earth Planet. Sci.* 29. [15] Hayne and Aharonson (2015), *JGR Planets* 120. [16] Sori et al. (2017), *GRL* 44. [17] Durham et al. (1992), *JGR* 97. [18] Marchi et al. (2016), *Nature Comm.* 7. [19] Dombard and McKinnon (2006), *JGR* 111. [20] Bland et al. (2012), *GRL* 39. [21] Castillo-Rogez et al. (2020), this meeting.