IMPACT BOMBARDMENT OF CERES

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Introduction: The internal structure of Ceres is unknown. Several different structures have been proposed, but the most prominent in the literature include either a dry or hydrated silicate core with an icy mantle [1]. These different structures will lead to different impact crater morphologies. With NASA's *Dawn* due to enter orbit around Ceres soon, we will start receiving the first images of craters on the surface, which can be used to infer the nature of Ceres' interior. Here, we use a statistical model to predict the largest impacts expected on Ceres through solar system history, and explore how crater morphologies for such impacts vary with internal structure.

Predicting impactor sizes: Using the statistical framework presented in [2], the number, sizes and velocities of impacts on Ceres were estimated. The size- and velocity frequency distribution of impactors in the asteroid belt were estimated using dynamical and collisional evolution models of terrestrial planet formation [3, 4] and as predicted for Ceres [5]. The disruption threshold for Ceres was set using the criteria from [6], although after 10^4 simulations of Ceres' impact history, no disruptive impacts occurred. Over the course of solar system history, Ceres could expect over 63000 impacts of impactors 300 m in diameter or larger. Over the same time period, on average Ceres would experience 3 impacts by objects one-twentieth its size (48 km), and have 1.3 impacts by objects one-tenth of its size (96 km).

The expected number of craters on Ceres today will also be dependent on the internal structure, as crater relaxation, especially near the equator, could remove evidence of craters > 4 km if they form in an ice layer [7].

Figure 1 shows an estimate of the number of craters formed on Ceres using the crater scaling parameters for ice from [8]. The model predicts around two craters larger than $\sim$ 700 km diameter. For small craters which form entirely in the ice mantle, this estimate is robust, but for larger craters (e.g. in which the core will play a role during the opening of the transient crater, or the curvature of the surface is significant), further modelling is required.

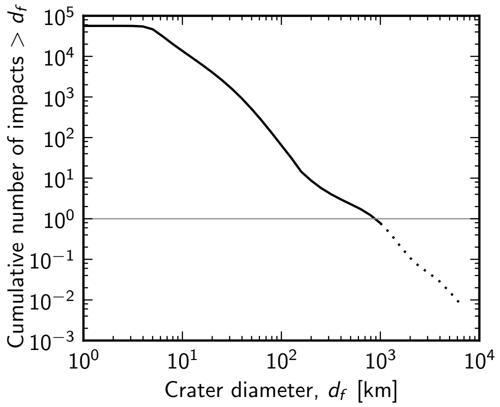

Figure 1: The cumulative number of craters on Ceres with diameters greater than d_f.

Impact modelling: The iSALE shock physics code [9–11] was used to simulate impacts into different possible internal structures for Ceres: (a) a dry silicate core with a radius of 369 km (using the ANEOS equation of state for dunite [12]) capped by an ice mantle (ANEOS equation of state for water), and (b) a hydrated silicate core of radius 426 km (using the ANEOS equation of state for serpentine [13]) capped by an ice mantle. The size of the cores was calculated to give a mass, surface gravity and bulk density consistent with those estimated for Ceres. A computational cell size of $\sim$ 3 km was used, which means that Ceres was represented by 160 cells across its radius. iSALE was used in its 2D, axisymmetric formulation to reduce computational costs (thus imposing a normal incidence impact angle), although full 3D simulations are ongoing. The silicate cores were assigned strength using the model described in [9], with parameters for dunite taken from [14]; the ice mantles were assigned strength using the model developed for icy satellites [e.g. 15]. Material was weakened after impact using the block model of acoustic fluidization [16]. A gravity field was assigned at the start of the calculation and, due to the large mass difference between the impactor and Ceres, was not updated during the calculation. Crater scaling for icy targets [8] suggests that to form a final crater $\sim$ 700 km in diameter, a projectile composed of ice around one tenth the diameter of Ceres is required to impact at 4 km s^{-1} (a typical impact velocity on Ceres [5]).

Results: Figure 2 shows some snapshots of two simulations of a 96 km diameter projectile impacting Ceres at 4 km s^{-1}: one with a serpentine core (left hand side) and one with a dunite core (right hand side). The top frame shows the initial condition, and highlights the extra thick-

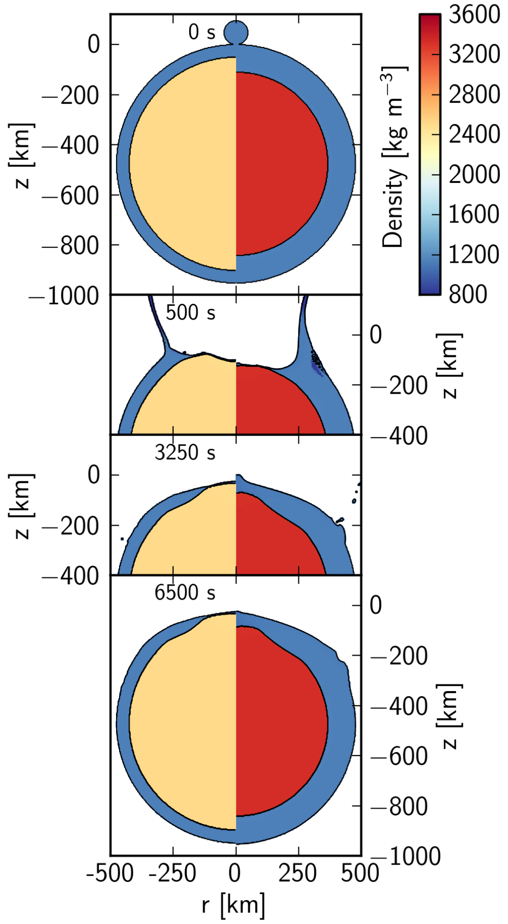

Figure 2: iSALE simulations of an impact of a 96 km diameter ice projectile at 4 km s^{-1} into two different target structures: on the left, a serpentine core (radius 426 km), and on the right, a dunite core (radius 326 km).

ness of the ice mantle in the dunite-core case. The second frame shows the opening of a transient crater; in both cases, the ice mantle is stripped away to expose the core, and in the serpentine case, a small crater is opened up in the core. In the third frame, the ice has flowed back into the centre and the core has uplifted beneath the centre of the crater. In the serpentine case, the core remains exposed (or only thinly covered) over a region $\sim$ 200 km in diameter. The bottom frame, and Figure 3, shows the scale of the final craters. The crater on the Ceres with a serpentine core has a rim-to-rim diameter of $\sim$ 690 km, and the crater formed on the Ceres with a dunite core has a rim-to-rim diameter of $\sim$ 760 km, consisent with the crater scaling estimate.

Discussion: Internal structure clearly plays a key role in determining final crater morphology. In large scale cratering events like those modelled here, no silicate material is ejected onto the surface, although some may be brought closer to the surface in a central uplift, beneath thinned mantle material. Modelling of larger impact events will place a constraint on the type of impact that could leave silicate ejecta on the surface, and thus be used in comparison with observations from *Dawn*. The uplift of core material will be observable in gravity anomaly measurements from *Dawn*, which can further be used to constrain the interior structure of Ceres.

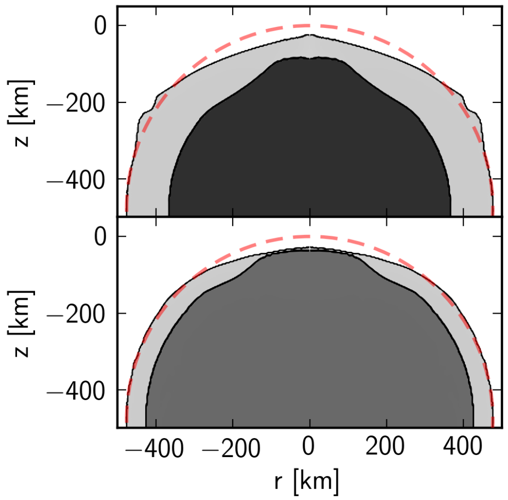

Figure 3: Final crater morphology compared to the pre-impact surface (red dashed line)

Further modelling will extend the parameter space over different impactor velocities, sizes and angles, and other internal structures (for example, a “convecting mudball” [17] or a homogeneous hydrated silicate body [18]).

References: [1] McCord, T. B. & Sotin, C. (2005) *JGR Planets*, 110:E05009. [2] Davison, T. M. et al. (2013) *Meteorit. Planet. Sci.* 48:1894–1918. [3] O’Brien, D. P. et al. (2006) *Icarus*, 184:39–58. [4] O’Brien, D. P. (2009) *Icarus*, 203:112–118. [5] O’Brien, D. P. & Sykes, M. V. (2011) *Space Sci. Rev.* 163:41–61. [6] Leinhardt, Z. M. & Stewart, S. T. (2009) *Icarus*, 199:542–559. [7] Bland, M. T. (2013) *Icarus*, 226:510–521. [8] Kraus, R. G. et al. (2011) *Icarus*, 214:724–738. [9] Collins, G. S. et al. (2004) *Meteorit. Planet. Sci.* 39:217–231. [10] Wünnemann, K. et al. (2006) *Icarus*, 180:514–527. [11] Amsden, A. A. et al. (1980) *Los Alamos National Laboratories Report*, LA-8095:101p. [12] Benz, W. et al. (1989) *Icarus*, 81:113–131. [13] Brookshaw, L. (1998) Working Paper Series SC-MC-9813 University of Southern Queensland, 12pp. [14] Ivanov, B. A. et al. (2010) *Geol. Soc. Spec. Pap.* 465:29–49. [15] Bray, V. J. et al. (2014) *Icarus*, 231:394–406. [16] Melosh, H. J. (1979) *J. Geophys. Res.* 84:7513–7520. [17] Bland, P. A. et al. (2013) *LPSC LXIV*, #1447. [18] Zolotov, M. Y. (2009) *Icarus*, 204:183–193.