THE GIANT CUE BALL: EFFICIENT RELAXATION OF CERES' CRATERS. A. J. Dombard[1] and P. M. Schenk[2], [1]Dept. of Earth & Environmental Sciences, University of Illinois at Chicago, Chicago, IL (adombard@uic.edu), [2]Lunar and Planetary Institute, Houston, TX.

Introduction: When NASA's Dawn spacecraft arrives at the dwarf planet Ceres in February 2015, it may find a very peculiar world. While the spectra of the surface do not indicate ice [1], its low bulk density suggests a high volatile content, presumably dominated by water ice. In addition, geophysical arguments suggest that Ceres is likely differentiated [2, 3]. Taken together, these lines of evidence suggest a rocky interior (dry or hydrated) surrounded by an icy mantle (covered in a less-volatile veneer of unknown thickness) [2]. Thus in terms of its basic structure, Ceres is more closely related to the icy satellites of the outer solar system than to the inner terrestrial worlds.

Prior to the close encounters of the icy Galilean satellites of Jupiter by the Voyager spacecraft, it was predicted that relaxation of topography of all horizontal scales would be so efficient that the surfaces would be topographically smooth, with only the freshest craters possessing any substantial topography [4]. Not borne out by observations, this prediction hinged on incomplete knowledge of the ductile rheology of water ice, but with improved information from laboratory experiments, we have previously demonstrated the observed relaxation *and* long-term retention of craters these satellites for reasonable thermal states [5].

For Ceres, McCord et al. [2] resurrected this idea of rapid relaxation of topography. Why topography on Ceres should relax while that on the icy outer satellites should be largely retained is to no small degree a product of the surface temperatures of these worlds. For the icy outer satellites, the surface temperatures are always less than half the melting temperature of the material, meaning that even for modestly high heat flows, some significant portion of the near surface will be too cool to flow ductily over geologic time scales and thus will be able to retain topography. In contrast for Ceres, the average predicted surface temperature (up to ~180 K [6]) is more than half the melting temperature, meaning all levels of an icy near-surface may flow appreciably over geologic time. Topographic relaxation may be rapid, rendering a very smooth Ceres. According to McCord et al. [2], "[a]lthough this remains to be properly modeled, a thick ice layer at Ceres' temperatures would relatively quickly relax any topographic feature." Here, we address the preamble to their conjecture and simulate crater relaxation on Ceres.

Methods: We use the same finite element techniques that we have used many times previously to explore crater relaxation [see 5 and 7 for examples]. We model one radial slice beneath the crater under a planar axisymmetric geometry. The domain extends 5 crater radii laterally and vertically, and the space is subdivided into 1500 elements, biased to concentrate more elements near the surface where the deformation occurs. Because of the similarity in composition and gravity to the mid-sized satellites of Saturn, we use the depth-diameter relationships measured for fresh craters on Rhea and Iapetus [7] to determine the initial depths of craters 10 and 100 km in diameter; we assume the crater's rim makes up 20% of that depth. We perform a thermal simulation to determine the temperature structure, piping the results into a mechanical simulation.

Thermal Simulation. Using thermal parameters of water ice, we determine the steady-state thermal structure of the equilibrium between an applied basal heat flux and surface temperature. Average surface temperatures at present on Ceres are estimated to vary from 180 K at the equator to 120 K at the poles [6]. Most of the surface, however, has temperatures of 160 K or higher, as such temperatures are realized at ~50° latitude or lower (~75% the surface area of Ceres). Only ~5% of the surface sees temperatures below 140 K (latitudes above ~70°). Thus, we consider temperatures of 140, 160, and 180 K. Surface temperature is not constant through time, however, because of increasing solar luminosity. Billions of years ago, the equatorial surface temperature would have only been ~160 K.

We estimate the current heat flux by considering the rock fraction of Ceres (around 75%). Assuming this rock has chondritic abundances of long-lived radionuclides, the surface heat flux is ~1 mW m^{-2}. Thus, we consider this heat flow with the 3 surface temperatures. Billions of years ago, heat generation would have been higher due to more abundant radionuclides, so we also consider the case of a heat flow of 5 mW m^{-2} with an equatorial surface temperature of 160 K.

Mechanical Simulation. Deformation is driven by the application of gravity with a constant downward acceleration of 0.276 m s^{-2}. The rheology is incompressible viscoelastic, again using the material parameters of water ice [see 5 and 7]. We track the relaxation using large-strain formalism and a scheme that always resolves the Maxwell viscoelastic time by a factor of 2.

We generally consider a water ice half-space for the ductile rheology, assuming the non-volatile surface veneer is too thin to affect appreciably the material strength profile. We also consider variants. For the 10-km crater, we add stiffening due to inclusion of 50%

by volume silicate particulates [8], such as might be expected with incomplete differentiation. For the 100-km crater, the high rock fraction of Ceres indicates a transition to a stiffer material at depths of 50-100 km (depending on densities), a transition within the flow field for a crater of this size [5]. Thus, we consider the case of non-creeping material at depths > 50 km.

Results and Discussion: For craters 10 km in diameter, only fresh craters at high latitudes should display substantial topography. Figure 1 shows profiles of this initial shape over a pure ice half-space and a modern heat flow value of 1 mW m^{-2}, after a simulated time of 100 Myr. Such craters found in equatorial regions (surface temperature of 180 K) are near completely relaxed, with only remnant rim topography. Mid-latitude craters (160 K) are strongly relaxed. Only high-latitude craters (140 K) are preserved, although there should be few of these craters because of the small surface area of Ceres at such high latitudes.

The inclusion of a high particulate content slows but does not prevent strong relaxation. For the equatorial surface temperature of 180 K, the dirty ice case retains of order 10% its initial topography after 100 Myr (compared to 1% for clean ice), still very strongly relaxed. Somewhat counter-intuitively, the craters relaxing under a thermal regime more appropriate to billions of years ago are still less relaxed, because even though the heat flow is a factor of 5 higher, the lower surface temperature retards the relaxation of small craters significantly. Such a less-relaxed ancient crater, however, will still end up strongly relaxed as it transitions into the warmer modern thermal regime.

As expected [5], larger craters relax more quickly. For a diameter of 100 km, all equatorial craters are strongly relaxed (effectively becoming palimpsests?) in < 10 Myr. Even polar craters of this size are very strongly relaxed over a time scale of 100 Myr (and near completely relaxed over 1 Gyr). Thus, only the very rare large, fresh impact crater on Ceres should be expected to be seen with significant topography.

The strong relaxation of large craters, however, may result in a useful tectonic signature. Strong relaxation is accompanied by relatively large surface stresses, resulting in brittle faulting [cf. 5]. For a compositional half-space, the stress pattern is tensile in the crater center (due to the uplifting floor) and compressive around the crater rim. On Ceres however, there is likely a material transition within the flow field of a relaxing large crater that can change the deformation. Though still near completely relaxed, our simulations of a 100-km crater with a ductily stiff material below 50 km depth display a different stress pattern because the subsurface flow field is compressed into a smaller space. The magnitude of the tensile stresses in the central zone is reduced relative to a half-space, and can sometimes be driven into compression, merging into the compressive zone around the crater rim. Exterior to the rim, a new tensile zone is created. Thus, examination of Dawn images of tectonic features associated with large, strongly relaxed craters coupled with simulations of relaxation may possibly be used as an indirect indicator of the thickness of the icy layer on Ceres.

Indeed, study of craters is critical to unraveling the structure and history of Ceres. Observations of crater morphology provide a direct test of an icy near-surface composition. An icy composition can affect morphology (simple vs. complex, depth/diameter ratios, etc., [9]), wherein initial crater depths are 60-70% shallower than on silicate worlds of similar gravity. Ceres is most similar in gravity to Iapetus and Rhea, and if Ceres is an ice-mantle world, then the simple-to-complex transition diameter should be roughly comparable (~8-12 km). This value is roughly half the observed transition for rocky Vesta [10] and a parameter that can be easily observed by Dawn. A confirmed icy mantle coupled with high surface temperatures then opens the door to crater relaxation studies, as only the freshest and highest latitude craters should display significant topography. With its expected smooth appearance, Ceres may be a giant cue ball in space.

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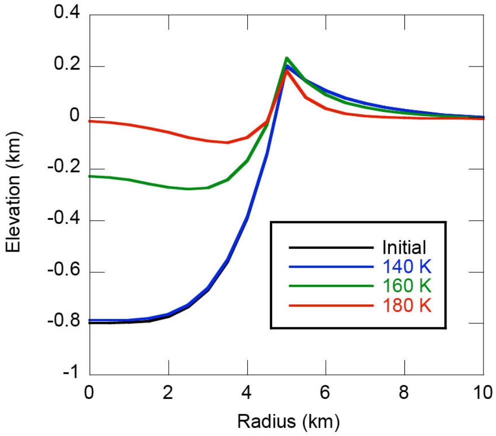

Figure 1. Elevation profiles of a crater over a pure ice half-space and heat flow of 1 mW m^{-2}, after 100 Myr. Surface temperature is indicated in the legend box.