DETERMINATION OF THE ACOUSTIC FLUIDIZATION PARAMETERS AS APPLIED TO IMPACTS ON THE ICY SATELLITES. V. J. Bray, G. S. Collins and J. V. Morgan. Department of Earth Science and Engineering, Imperial College London, Exhibition Road, London, SW7 2AZ, United Kingdom. veronica.bray@imperial.ac.uk

Introduction: Impact craters on the icy satellites offer direct probes of the moons' subsurface, and may hold the key to understanding their geologic evolution. It has been suggested that two transitions in crater shape that occur with increasing crater diameter reflect rheologic changes at depth within the moons [1]. To test this hypothesis we performed some numerical simulations of impacts on the icy satellites. This new work builds on earlier numerical studies [2, 3], and aims to better constrain the impact process and the effect of rheologic target variations on crater depth and morphology.

Background: Complex craters on the icy satellites differ in several important ways to those on the terrestrial planets and rocky moons. Simple craters generally have similar depth-to-diameter ratios to their rocky counterparts (Fig. 1) [1]; however, the simple-to-complex transition occurs at a smaller diameter than rocky bodies with similar gravity, and complex craters on the icy satellites are much shallower than those formed on rocky bodies. Moreover, some complex craters on the icy satellites have distinctly different morphologies from similar sized craters on silicate bodies with similar gravities, and their mode of formation remains uncertain.

A quantitative model for impact crater formation on the terrestrial planets now exists [4], which relies upon the acoustic fluidization of rock debris [5]. This fluidization occurs due to the strong vibrations initiated by impact-generated stress waves; however, it is also dependant on the material characteristics of the target. The similarity between simple crater profiles on Ganymede and the moon (Fig. 1) suggests that the near-surface rheology of the icy satellites is similar to that of the terrestrial planets and moons. This is supported by experiments into the strength properties of water ice at low temperature [6], which reveal that ice at 110K has a similar rheology, but lower strength, when compared to silicate rocks. It seems likely, therefore, that the acoustic fluidization model of impact cratering also applies to the icy satellites.

The added complexity of large craters in ice is most likely due to the complicated rheology of ice at temperatures close to the melt temperature, and hence the thermal profile within the icy lithosphere on each of the Galilean satellites. However, to deconvolve these effects from the effects of the underlying impact process, as it is understood to occur on rocky bodies, we must first constrain parameters controlling acoustic fluidization in ice [3]. Our research aims to define a specific range for these parameters so that cratering on the icy satellites and other bodies can be more accurately modeled. Once these parameters are known the effect of the more complex rheology of ice at higher temperature and rheologic variations within the target may be investigated reliably.

Method and Model Assumptions: Our numerical modeling work used the SALE-3MAT hydrocode [4], a multi-material, multi-rheology extension of the SALE hydrocode [7], which is very similar to that used in prior modeling work on the icy satellites [3]. Our approach was to simulate vertical collisions of ice impactors into an ice target. Suites of models were performed with different acoustic fluidization parameters (γ_β and γ_η—see below) and target cohesions (Y_0). The resultant profiles were then compared to existing DEM profiles of ganymedian craters [e.g. 8, 9] to find the best morphological comparison and ergo the most suitable set of acoustic fluidization parameters. Our work concentrates on the simulation of pristine craters, assuming no subsequent viscous relaxation.

Impactor type and velocity. Based on the local populations of cometary/meteoritic bodies, it is assumed that the majority of craters on the Galilean moons were created by Jupiter Family Comets (JFCs) [10]. It was therefore most appropriate to model our projectile properties on JFC composition. The Tillotson equation of state for ice was used for the impactor and target. JFCs are thought to impact Ganymede at an average velocity of 21.5 km s^{-1}. However, velocities of this scale considerably increase the run time necessary for the simulations due to the high resolution required to fully resolve the relatively small impactor. As a compromise, a larger impactor and smaller velocity (10.5 km s^{-1}) were used.

Initial target conditions. In the first instance, we decided to simulate the target conditions on Ganymede, with a gravity of 1.43 ms^{-1}. Morphological transitions thought to be associated with the moon´s internal rheological layering occur at crater diameters of ~26 and ~150km on Ganymede. So as to remove rheologic variations as a variable, a range of impactor diameters were chosen to produce simulated craters with a final diameter between 1 and 20km.

Ganymede was chosen over Europa and Callisto for several reasons. The relative paucity of impact craters on Europa and the assumption that their morphology is partly dictated by the presence of a subsurface ocean makes it unsuitable for this comparison. Furthermore, a large majority of small impact craters on Europa appear to be secondary craters [11]. Profiles of craters on Callisto are also unsuitable as its ancient surface holds craters that are heavily affected by ´space gardening´ and viscous relaxation. Ganymede´s relatively fresh surface allows craters less affected by relaxation to be compared to, thus closer representing the original crater shape.

To simplify our preliminary model, we ignored the fracturing process; damage accumulation was not computed. The strength of ice as a function of pressure was instead approximated using a single equation, fit to experimental data on the frictional properties of ice at ~100K [6]. Variations on this strength model were considered, primarily by varying the strength of ice at zero pressure Y_0. The model was further simplified by ignoring the effects of porosity and assuming a uniform temperature of 100K for the near-surface (upper 10 km). The strength of the target was controlled primarily by the acoustic fluidization model.

Acoustic Fluidization model. The vibrations that cause a target to become fluidized are transmitted as sound waves using rock-to-rock contacts [5]. Sporadic failure is initiated wherever the overburden pressure is approximately cancelled by the strength of the rarefaction waves. This process allows a normally rigid material to flow as a fluid over a short time scale (i.e. 100 s). A simple approximation of the effects of acoustic fluidization, known as the block model [12], is implemented in SALE-3MAT [4]. In this model, the amount and longevity of the acoustic fluidization experienced by the target during crater formation is controlled by two parameters: the decay time of the pressure vibrations τ and the dynamic viscosity of the fluidized region η. Simple linear prescriptions relate these parameters to the projectile size (R_p) and bulk sound speed of the target (c = 4 km s^{-1}), via two constant parameters: γ_β and γ_η [4]. The decay time of the acoustic vibrations is given by:

$$\tau = \gamma_\beta \frac{R_p}{c}, \quad (1)$$

and the dynamic viscosity of the fluidized region is given by:

$$\eta = \gamma_\eta c R_p \quad (2)$$

Resolution The effects of total mesh size and resolution on the shape of the final crater were investigated prior to the main experiment to ensure no interference from the mesh itself.

Preliminary Results: Figure 1 shows a comparison between depth/diameter measurements for craters on Ganymede and our preliminary model results. The first suite of models (gray squares) successfully simulates the simple-to-complex transition but produces final craters that are too deep. The second suite (gray triangles), which assumes a lower cohesion of the ice and less acoustic fluidization (see caption), appears to be more promising, but further simulations are required to better match the observational data.

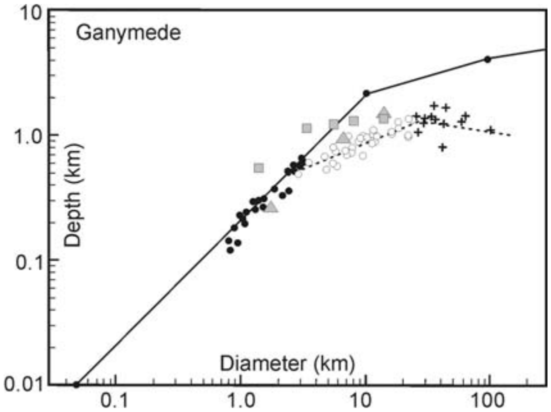

Figure 1: *Depth-diameter measurements for craters on Ganymede taken from Schenk* [1]*: solid line is for Lunar craters, dashed line is least squares fit through data, solid dots are simple craters, open circles are complex (central peak) craters, and crosses are central pit craters. Gray squares and triangles represent results from numerical modelling (squares: Y_0 = 0.05 MPa, γ_β* = 1250, γ_η = 0.001; *triangles*: $Y_0 = 0$, γ_β = 700, γ_η = 0.001)

Summary: Constraining the acoustic fluidization parameters for impacts into icy targets is the first step in the development of a quantitative model of cratering on the icy satellites. With further simulations we hope to (1) produce a quantitative model of simple-to-central peak craters where variations in target rheology have no influence on crater size and shape; and (2) by considering different thermal profiles in the target, simulate the effect of subsurface temperature-dependent rheology variations on larger impact crater morphology.

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