CATASTROPHIC DISRUPTION OF ICY CORE-MANTLE BODIES IN THE LABORATORY.

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Introduction: The population of the Kuiper Belt consists of a collection of icy bodies found outside the orbit of Neptune. While the majority of these objects are relatively small, more and more Pluto-sized bodes are being discovered [1] which points to a significant population of this category of bodies existing in the Kuiper belt and the Scattered Disk.

The large number of smaller bodies that are predicted in the Kuiper Belt indicates that the larger objects such as Pluto will undergo impacts from the smaller bodies [2] at velocities on the scale of a few km s^{-1} [3]. The collisional disruption rate of these objects is required to model their size distribution and lifetime as well as their collisional evolution, and this requires a knowledge of Q^* (the critical disruption energy) at these size scales in addition to the impact flux on these objects. The value of Q^* can be obtained in experimental studies. However these results must be scaled to apply to larger bodies in space and also take into account the energy needed to disperse a disrupted body against gravitational reassembly. Q^* for small-scale targets (on the order of centimetres) can be determined in the laboratory. These lab experiments can provide general insights as well as fixed calibration points for the modeling which can then be extrapolated to all scales.

The measured density of Pluto (2.05 g cm^{-3} [4]) implies a mixed rock:ice content for these bodies. It is also suspected that Pluto possesses a differentiated structure with a layer of ice covering an ice-silicate core [5]. If Pluto is taken as typical, then this composition and structure need to be reflected in any detailed modeling of the collisional evolution of these bodies.

Accordingly here the results of a programme of lab experiments are reported. They use a variety of ice-silicate targets to both determine Q^* and examine the dependence of the results on the presence of an overlying ice mantle.

Method: Previous experimental work has been carried out using ice-silicate cylindrical targets with the same density as Pluto [6]. Here, in order to take into account the suspected differentiated structure a process has been developed for constructing layered targets with roughly the same general properties as Pluto.

First, a mixture of sand and water was poured into a small spherical mould, in proportions of 60% sand to 40% water by mass. The moulds were frozen for one day at approximately -18 °C, and then the mould was cut away producing frozen spherical ice-silicate cores approximately 39mm in diameter. These cores have an average density of 1.97 ± 0.08 g cm^{-3}, making the core properties very close to that of Pluto. The cores were then dipped into liquid nitrogen and water in succession; the nitrogen causes the water on the core to freeze instantaneously allowing a mantle of ice to be slowly built up on the outside of the core. Depending on what is required of the target the mantle can be made to a thickness of anywhere between 1mm to 7mm, giving a mantle thickness to core radius ratio of 2.5 - 35% varying from thin to thick shells.

These targets are then subjected to hypervelocity impacts using the two-stage light gas gun at the University of Kent. [7]. The projectiles were either 0.8mm diameter stainless steel or 1mm diameter titanium spheres, the speed of which were varied in order to produce a range of impact energies. These impact energies are then divided by the target mass to produce the energy density Q (J kg^{-1}) for each impact.

After each shot the mass of the largest remaining fragment of the target is measured (M_f) and compared with the total mass of the target before it underwent impact (M_o).

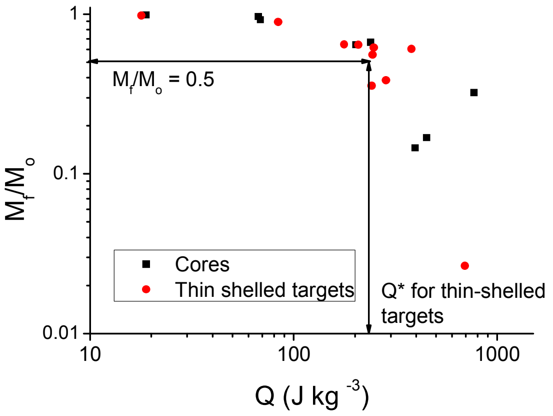

Figure 1: Comparison of stainless steel shots on unlayered sand:ice cores and stainless steel shots on cores covered with a thin layer of pure ice.

Results: In the first shot program 17 shots were made using stainless steel projectiles to impact both pure cores with no ice mantle and cores with a thin surface layer of ice (average thickness of 2mm ± 0.96mm, or 5% of the core radius). The results of this program are presented in Figure 1, which plots the ratio of the values of M_f/M_o against the energy density for each shot.

The energy densities covered a range from 17.9 J kg^{-1} to 768 J kg^{-1}. The critical energy density for disruption is defined as the value of Q which will yield an M_f/M_o ratio of 0.5.

As can be seen from Figure 1 there is very little difference in the catastrophic disruption energy of pure cores without ice mantles and cores with only thin mantles added. Q^* for the stainless steel shots on the thin shelled targets is 210 ± 25 J kg^{-1}. Note that given the stainless steel projectile diameter of 0.8mm the thickness of the ice layer normalized to projectile diameter is 2.5 ± 1.6.

In the second shot program 21 shots were made using titanium projectiles to impact cores with a thin layer of ice (as defined above) and cores with a thicker layer of ice (average thickness of 6mm ± 0.9mm, or 30% of the core radius). The results of this program are shown in Figure 2.

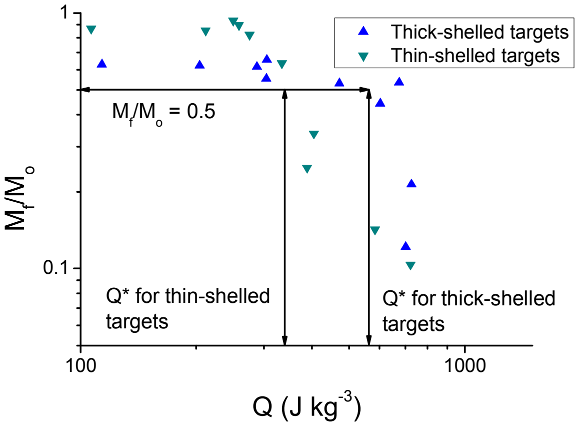

Figure 2: Comparison of titanium shots on cores with a thin layer of pure ice and titanium shots on cores with a thick layer of pure ice.

Figure 2 shows a different behaviour than that seen in Figure 1; increasing the shell thickness results in it being easier to reduce the surviving target mass at low value of Q suggesting the thick ice shell requires less energy to damage it and remove mass than does a pure core. However, at higher values of Q it becomes harder to disrupt the target entirely, resulting in a higher value of Q^* for thick mantles. Q^* for the titanium shots on thin-shelled targets (ice layer thickness to projectile diameter ratio of 2 ± 0.96) is 320 ± 30 J kg^{-1}, while Q^* for the titanium shots on thick-shelled targets (ice layer thickness to the projectile diameter ratio of 6 ± 0.9) is 570 ± 50 J kg^{-1}.

Discussion: Previous work [6] determined the catastrophic disruption of sand:ice cylinders using 1mm and 2mm diameter copper projectiles; this work determined that Q^* for the homogenous sand:ice material was 209 ± 30 J kg^{-1}. This value is in very good agreement with the value derived from the stainless steel shots on the spherical homogenous sand:ice cores and the thin-shelled targets. This indicates that ice mantles comparable in thickness to the projectile diameter have little effect on the disruption process. However, the value of Q^* determined from the titanium shots on thin-shelled targets exceeds this value by 50%, indicating that the projectile material may have an effect on the critical energy density; Copper and stainless steel have similar high densities (8.96 g cm^{-3} and 7.83 g cm^{-3} respectively) compared to titanium (density 4.51 g cm^{-3}). More work is required to discover whether or not this effect continues to significantly lower densities such as 2 g cm^{-3} similar to that of Pluto-type objects.

When the shell thickness is the only factor being varied, targets with thicker shells (> 6 times the projectile diameter) yield a Q^* value that was almost 80% greater than that for thin-shelled or homogenous targets. This result is in agreement with a recent study [8] into impacts on core-mantle bodies made of other materials (glass core-gypsum mantle) which also found that mantle thickness influences the outcome of disruption experiments.

Conclusion: A study has been carried out into how the addition of an ice layer to a homogenous body affects the energy density required to disrupt it during hypervelocity impacts at speeds of several km s^{-1}. While a thin ice shell similar in depth to the projectile diameter has little to no effect on the required disruption energy, a thicker ice shell increases the energy density required to disrupt a body by almost a factor of two. In addition we find that there is an influence of projectile density on disruption energy in that denser projectiles produce smaller Q^* values, and that when thick mantles are present increased mass loss at sub-critical energy densities occurs.

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