SURVIVAL OF TERRESTRIAL MATERIAL IMPACTING THE LUNAR SURFACE.

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Introduction: The lunar surface has been impacted by a plethora of hypervelocity projectiles over its lifetime, leading to the heavily cratered surface we see today. This rich impact history is epitomised by the Late Heavy Bombardment (LHB), a period circa 3.9 Gyr ago where the inner planets experienced frequent large impacts. During this time, Earth would have experienced many hypervelocity impacts, ejecting terrestrial material at velocities great enough to surpass escape velocity and take up Moon-crossing orbits. This has led to the proposal that such ejecta could be preserved on the lunar surface as terrestrial meteorites [1], if they survive impact. The lack of atmosphere, tectonics and the low surface gravity, are all factors that enhance the likelihood that the Moon might still preserve a record of the early Earth, of which there is no other such record in the Solar System. In some regions of the lunar surface, as much as 510 kg km^{-2} of terrestrial material may have impacted [2], with a globally averaged concentration of terrestrial material between 1–2 ppm.

Previous hydrocode modelling work has been carried out to characterise the likely survival of projectiles impacting the lunar surface, using ANSYS AUTODYN [3]. This work considered solid, cube-shaped, basalt/sandstone projectiles impacting an unconsolidated sand target layer at 2.5 km s^{-1} and 5 km s^{-1} with varied impact angles. Here we update and improve previous analysis of terrestrial meteorite survival, using the two-dimensional version of the iSALE shock physics code [4-6]. We consider the effect of projectile shape and the equation of state (EOS) used, as well as a more accurate lunar surface analogue including porosity.

Methods: We simulated nonporous sandstone (sst) projectiles vertically impacting a basalt target layer at 5 km s^{-1} (the upper limit found via analytical methods by [2] for vertical impact speeds of terrestrial meteorites on the Moon) in cylindrical geometry. The impactor was modelled in three different shapes: (1) 0.5 m diameter spheroid, (2) 0.5 x 1 m oblate spheroid and (3) a 1 x 0.5 m prolate spheroid. An oblate spheroid describes a flattened spheroid, where the horizontal diameter, parallel to the target surface, is longer than the vertical diameter. Prolate spheroids are the opposite. Porosity of the target basalt layer was zero (solid), 30% and 70% for different simulations, using the epilson-alpha porosity model [6]. The basis for a 30% regolith porosity stems from Apollo samples with intragranular porosities in lunar regolith of 21-32%, rising to 52% when including intergranular porosities [7]. An upper limit of 70% porosity was chosen based on the suggestion that a location in the vicinity of 50º W, 85º S represents the best location to search for terrestrial material on the Moon [2]. This is the general area where the LCROSS mission impacted the lunar surface and suggested a surface porosity of >70% [8].

The solid component of the sandstone and basalt were modelled using equation of state tables derived using the analytical equation of state package (ANEOS). The strength of the impactor and target materials was modelled using [5]. Each model used 20 cells per projectile radius (CPPR), double that used by [3], with tracer particles placed within the projectile every two cells. These tracers track material initially located in the cells in which they are placed and record peak pressures and temperatures of this material during the simulation. Simulations used lunar gravity (1.62 m s^{-2}), a surface temperature of 273 K and were run until peak pressures within the projectile stopped increasing (1.5 ms).

Results: Five models were considered (Table 1): (a) repeated model from [3], cylindrical sst projectile into sand, (b) spheroid sst into basalt, (c) spheroid sst into 30% porous basalt, (d) spheroid sst into 70% porous basalt, (e) oblate spheroid into basalt, (f) prolate spheroid into basalt.

Table 1: Mean and median peak shock pressures for projectiles in models.

Model	Mean Peak Pressure (Gpa)	Median Peak Pressure (Gpa)
(a)	11.6	10.0
(b)	18.2	19.3
(c)	13.2	13.2
(d)	5.9	5.6
(e)	26.0	27.7
(f)	9.8	7.5

Comparing (a) and (b), shows how shock pressures increase with the introduction of a solid basalt target layer, with mean peak pressures increasing by over 40%. However a 30% porous basalt layer can be seen as comparable to the sand layer used in [3], according to mean peak pressures. Peak shock pressures in the projectile decrease with increasing target porosity (Fig.1c and 1d), as low as 0.675 GPa in the trailing half for model (d). The highest shock pressures are found in model (e), at 42 GPa, showing how shape of the projectile dramatically effects the survivability of the material. Model (f) indicates how prolate projectiles survive better than cube (a), spheroid (b) and oblate (e) projectiles, even when impacting into sand, in the case of model (a). Figure 2 displays how the trailing half in a prolate projectile experiences a higher proportion of very low shock pressures compared to a spheroid. Therefore, more material has a higher probability of surviving with very little alteration due to shock.

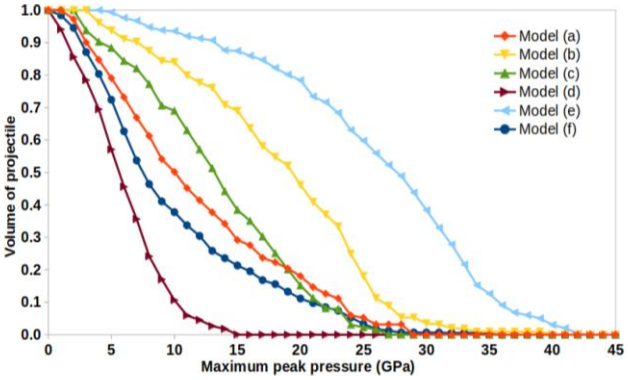

Fig. 1: Maximum peak shock pressures as a function of volume for projectiles in models (a)-(f).

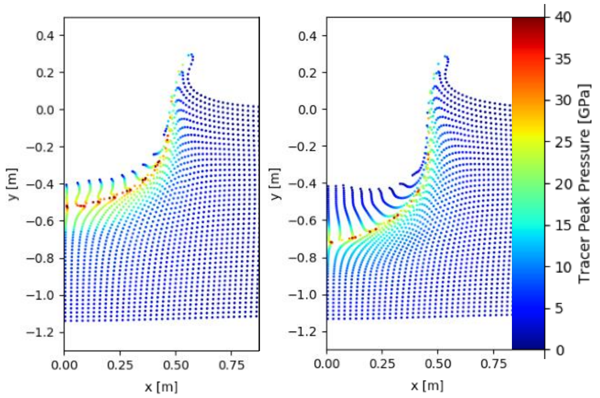

Fig. 2: Tracer map of model b (left) and f (right) displaying peak pressures, after the shockwave has reached the back of the projectile.

Conclusions: Even when considering a more dense target than used by [3], peak shock pressures remain low enough for significant proportions of nonporous impactor material to potentially survive impact. Model (a) found very similar, yet lower, median peak pressures to the same simulation in [3] (10.0 vs. 12.8 GPa, respectively). Similar conclusions can be drawn from this work to that conducted in [3], however this work covers a wider range of parameters relating to the materials and therefore expands upon the range of terrestrial meteorites that could survive impacts. Although [3] additionally considered angled and a lower velocity impacts of 2.5 km s^{-1}, these parameters are well researched and known to increase the likelihood of survival. Model (e) produced the highest peak pressures, however they did not exceed 22 GPa for ~30% of the projectile. Quartz in a nonporous sandstone would only be heated to ~600 K at these pressures [9], translating to weakly-altered [10], but intact terrestrial material. Particularly, terrestrial sedimentary impactors with shapes elongated in the direction of impact will produce a higher proportion of weakly shocked material, more likely to survive. Porosity in the target has a great effect on survivability, as mean peak pressures substantially decrease in the projectile with increasing porosity. In the case of a target area on the lunar surface similar to that described by [2] as the most likely area for large amounts of terrestrial material to impact, the 70% porosity greatly enhances the probability of large amounts of intact, weakly-shocked materials to be found. Results from model (d) suggest that ~90% of the impactor would experience peak pressures <10 GPa, which would be low enough for the survival of other constituents, such as phyllosilicates, volatiles and potential biomarkers [3,9,11]. Importantly, all of the impactors in these models survive, at least in the sense that the majority of the rock does not melt or vaporise. More simulations need to be run to include porosity of the projectile, which will dramatically lower the critical pressure required for melting, and a range of impact angles, in order to gain a more accurate understanding of the fraction of terrestrial meteorites that may have survived impacting the lunar surface. Comprehensive analysis of impactor survival requires consideration of peak temperatures as well as peak pressures due to significant shear heating experienced by the impactor during low-velocity impacts [12], which will be explored in future.

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