EPSC Abstracts
Vol. 11, EPSC2017-251-2, 2017
European Planetary Science Congress 2017

Quantification of shock-induced melting and its distribution in the Ejecta

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Abstract

In contrast to lunar regolith, which is dominated by impact melt particles (agglutinates), samples from the asteroid Itokawa (25143), collected by the Hayabusa mission, exhibit a strong deficit in agglutinates. To investigate the amount of shock-induced melting and its distribution in the ejecta we simulate hypervelocity impacts into targets with varying gravity and quantify the amount and distribution of generated melt that is ejected. We find that even at relatively low impact velocities and high target porosity (representing asteroidal condition) a significant amount of melting occurs.

1. Introduction

The surfaces of atmosphereless bodies are subject to a continuous flux of impactors ranging from micro-meteoroids to large, crater-forming objects. Independent from the size-scale hypervelocity impacts generate shock waves that lead to distinct shock metamorphic effects in silicates including melting and the formation of amorphous glasses. On the Moon, impact gardening and space weathering have formed a regolith layer dominated by impact melt particles (agglutinates) [1]. The ejecta thickness on the Moon generally decreases with increasing distance from the crater. The regolith layer on the asteroid Itokawa (25143) directly sampled by the Hayabusa mission [2] shows a distinctly different picture: dust particles exhibit different (solid-state) shock features, but agglutinates appear to be rare. The deficit in impact melt in the Itokawa regolith may be explained in two ways: (1) the relatively low impact velocities on asteroids in comparison to the Moon generate shock pressures insufficient to cause melting; (2) the vast majority of impact generated melt is ejected and escapes the low gravity environment on asteroids. (1) can be ruled out as several studies have shown that shock melting and agglutinate-like particles occur in granular target material even at impact velocities as low as ~ 2.5 km s^{-1} [1,3,4]. This is because the high porosity in regolith reduces the critical pressure for shock melting significantly [5]. Here we investigate the second option, that most impact melt is ejected and escapes the low-gravity field. We compare the results for the conditions on an asteroid with the melt distribution in the ejecta for lunar conditions.

2. Methods

We use the iSALE shock-physics code [6] to simulate hypervelocity impact processes. In a first step we validated our model against laboratory experiments. In a second step we conducted a suite of impacts in a low gravity environment (Table 1). To account for target porosity and its effect on the reduction of the critical shock pressure required for melting we used the ε–α compaction model [6]. The amount of material that experienced a certain shock pressure was measured by recording the peak shock pressure with tracers.

Table 1: Model Setup

Model Type	Resolution (CPPR)	Impact velocity (kms^{-1})	Porosity (%)	Thermodyn. Behaviour (ANEOS)
Shock Vol.	10/20	2.5–12.5	0-60	Aluminum/ Quartz, Basalt [8,9]
Ejecta	60			

3. Results

Figure 3 shows the results of impact models in a low gravity regime (g = 0.0162 m s^{-2}). Note that gravity does not affect melt production and has little effect on the ejection mechanics. However, gravity effects whether ejected material can escape the gravity field of an asteroid and the distribution of material expelled from a crater forming an ejecta blanket (e.g. on the Moon). To calculate the escape volume on an asteroid, we used the real escape velocity on Itokawa of ~ 0.2 m s^{-1}. We also verified that the amount of melt relative to the size of the impactor is constant. Figure 3 shows the percentage of melt that is ejected and escapes the gravity field (ejection velocity > escape velocity) as a function of impact velocity and target porosity. At zero porosity (brown line) no melt is generated at 5 km s^{-1}. At 7.5 km s^{-1} almost 70% of the generated melt escapes the gravity field. At higher velocities more melt is generated, but the relative amount of escaped melt decreases. In fact the vast majority of melt that does not escape the asteroid remains inside the crater and is not ejected. This is most likely due to the fact that we consider vertical impacts only, which is a limitation of the 2D cylindrical geometry in our models. Material that is highly shocked and located in a cone-shaped volume underneath the point of impact is displaced into the target, lining the crater wall as a thin veneer, but is not ejected. This may change significantly in case of more realistic oblique impacts. For porosities ⩾20%, melt is already generated at an impact velocity of 2.5-5 km s^{-1}, but the escape melt volume also decreases with increasing impact velocity.

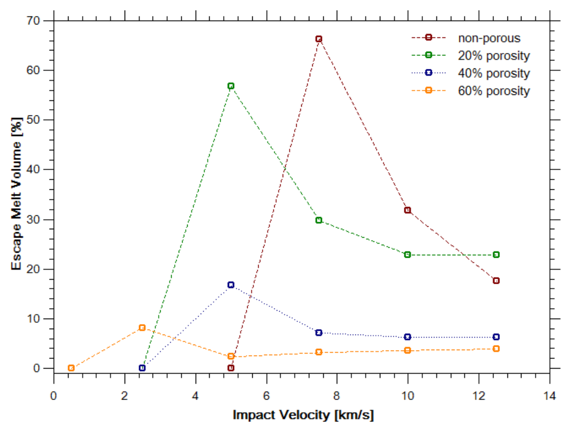

Figure 3: Percentage of melt that is ejected and escapes the gravity field of an Itokawa-like asteroid relative to the total amount of generated impact melt as a function of impact velocity. According to [7], we assume for the critical peak pressure for melting ~ 60, 30, 15, and 5 GPa for 0%, 20%, 40%, and 60% porosity, respectively. The projectile diameter is 50 m. We assumed a basalt ANEOS for both target and projectile.

4. Conclusions

Our models are in excellent agreement with observations from laboratory experiments, building high confidence in our results. Although our estimated critical shock pressures for melting of porous basalt may be questionable, different critical shock pressures would only cause a small shift of the lines shown in Figure 3. Given the fact that ejection dynamics change significantly in case of oblique impacts, the biggest limitation is the vertical impact simplification. Overall, our study demonstrates that a significant amount of melting occurs at relatively low impact velocities if the target is porous. Our models also predict that in case of vertical impacts a significant amount of the generated melt remains inside the crater and is not ejected. Currently, we are investigating the distribution of shock melting in the ejecta with increasing distance from the crater for impact scenarios that are typical on the Moon.

Acknowledgements

We acknowledge the developers of iSALE, VIMoD and pySALEPlot.

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