JETTING DURING OBLIQUE IMPACTS. S. Wakita[1*], B. C. Johnson[1], and T. M. Davison[2], [1]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN, USA, [2]Department of Earth Science and Engineering, Imperial College London, London, UK ([*]swakita@purdue.edu).

Introduction: Early in an impact, highly shocked high velocity ejecta are squirted out from the region where the projectile contacts the target. We call this intense process "jetting" [1]. Previous work investigated the jetting process by theoretical [e.g., 1-4], experimental [e.g., 5-6], and numerical methods [e.g., 7]. In this work, we define jetted ejecta as any material with an ejection velocity exceeding the impact velocity. Although the amount of jetted material is rather limited, a few percent of the impactor mass at most, jetting is an important impact process. Jetting at grain contacts can cause melting of silicates experiencing relatively low bulk shock pressures [2]. Planetesimals collisions may trigger chondrule formation via impact jetting [8]. Jetting during impacts into icy bodies results in vaporization and loss of icy materials [9].

It is well known that most impacts are oblique with the average impact angle being 45º [10]. Jetting during oblique impacts, however, remains poorly understood. Thin plate theory is often used to describe the jetting process [1, 3]. Using thin plate theory, [4] estimated oblique impacts produce more jetted material than head-on impacts. Impact experiments, however, indicate that we cannot apply thin plate theory to the impact of spherical impactor [6, 11]. Here we simulate jetting during oblique impacts for the first time and explore how impact angle affect jetting efficiency.

Methods: We perform head-on and oblique impact simulations using the shock physics code iSALE-3D [12, 13]. We simulate impacts of a 1 km diameter (D_{imp}) dunite impactor [14] onto a flat target of the same composition. Our resolution is 100 cells per projectile radius. We vary impact angles from 90º (vertical) to 15º by 15º increments and simulate impacts at velocities (v_{imp}) of 2, 3, and 5 km/s. We use Lagrangian tracer particles to track the ejecta's position, velocity, and temperature. A tracer is considered as jetted when its velocity exceeds the impact velocity; the vertical component of its velocity is positive; and it is above the surface of the target.

Results: Figure 1 represents the distribution of ejecta from oblique impact with an impact angle of 45º at 3 km/s. During an oblique impact, jetted material is directed downrange. This is different from the symmetrical distribution of ejecta from head-on impacts (not shown here). Figure 2 shows that the jetted ejecta are distributed only in downrange direction, azimuth less than 90º, in the case with an impact angle of 45º. Even higher velocity ejecta are the ejecta become more concentrated in the downrange direction.

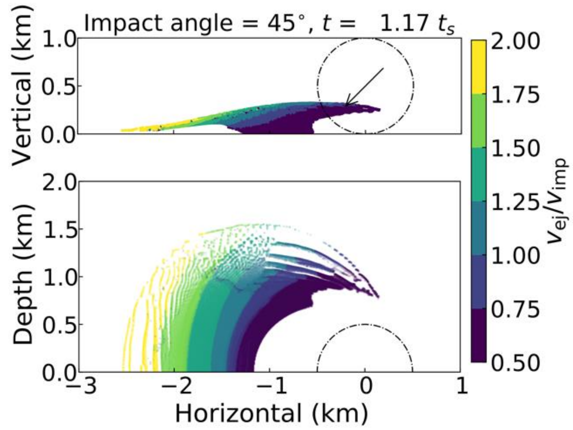

Figure 1: Tracers colored according to their velocity 1.17 t_s after a 45º impact at 3 km/s, where $t_s = D_{imp}/v_{imp}$ is the characteristic time for contact and compression. Note we only plot tracers ejected at velocities $v_{ej} > 0.5v_{imp}$. Top panel represents the cross section and bottom one does the birds eye view. Dashed lines depict preimpact location of the impactor and the arrow in top panel shows the direction of the impactor.

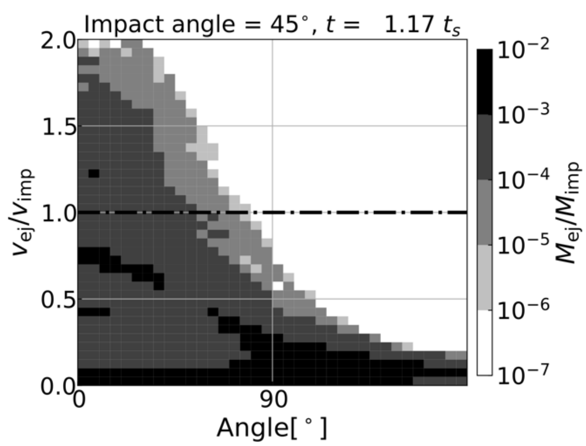

Figure 2: Heatmap of ejecta as a function of ejecta's velocity and azimuthal angles. Note that we measure the azimuthal angles from the direction of the impactor; the downrange direction is 0º. Bins are shaded according to ejecta's mass (M_{ej}) normalized by the impactor's mass (M_{imp}) as indicated by the color bar.

Figure 3 shows how the mass of jetted material depend on impact angle. The jetted mass from head-on impacts is about 1% of the impactor's mass. The oblique impacts of 45º, however, produces five times the jetted mass produced by the vertical impact. Note that less than 10^{-3} impactor masses are jetted during the 15º impact at 3 km/s. [5] indicated the critical wedge angles depends on the impact angles; the grazing impacts has lower critical wedge angles than head-on ones. Considering this, we will explore the reason of lower jetted mass in grazing impacts. Although there is a difference when we change the impact velocity (see the solid line in Figure 4 for the case of 5 km/s), the amount of jetted material from oblique impact is always larger than head-on impacts of 90º except in the case of grazing impacts.

While ejecta from the target dominate the jetted mass of 90º and 75º impacts, most jetted material originates from the impactor when the impact angles is below 60º (see Figure 3). The fraction of the impactor to the total jetted ejecta is 19% for the head-on impact and 83% for the oblique impact of 45º. This result is consistent with experimental results of [5] who found the jetted materials from the impactor dominates the jet in case of oblique impacts.

Implications for Chondrules and Discussion: Chondrules are previously molten particles found in chondritic meteorites [15]. Jetting can result in melting and vaporization during relatively low velocity impacts [2, 3, 9]. Thus, impact jetting has been proposed as a chondrule formation mechanism [8]. Comparisons to higher resolution (1000 cells per projectile radius) two-dimensional simulations suggest that our three-dimensional simulations are somewhat under resolved. Although our quantitative results may change with higher resolution, we can still explore how impact angle affects the amount of jetted melt, potentially chondrule forming material produced during accretionary impacts. We find that about 60% of jetted ejecta are partially molten (i.e., have a post release temperature greater than 1373 K) in the case of v_{imp} = 5 km/s (see Figure 4). Our results show the melt fraction is almost constant regardless of impact angles. This contrasts with the results of [4], which indicated that grazing impacts produces more jetted melt than vertical impacts. Given that the oblique impacts produce more jetted ejecta than head-on impacts, oblique impacts will produce more jetted melt and potentially chondrule forming material than head-on impacts. Future work will focus on providing more robust quantitative estimates of the effect of impact angle on the amount of jetted melt.

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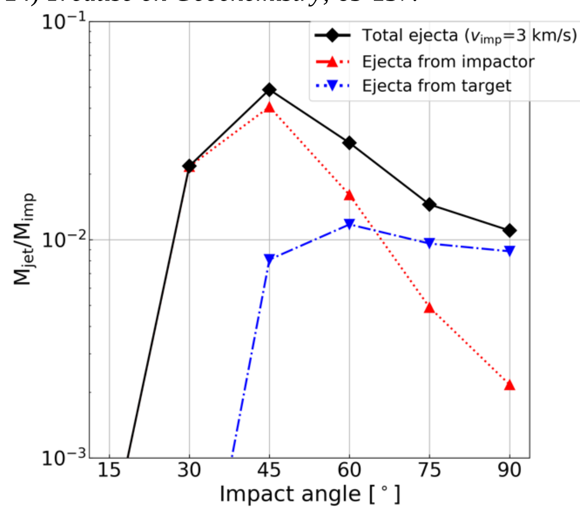

Figure 3: Jetted mass as a function of impact angles with v_{imp} = 3 km/s. Each line represents the jetted ejecta from target (blue dot-dashed line), the impactor (red dotted line), and the total (black solid line).

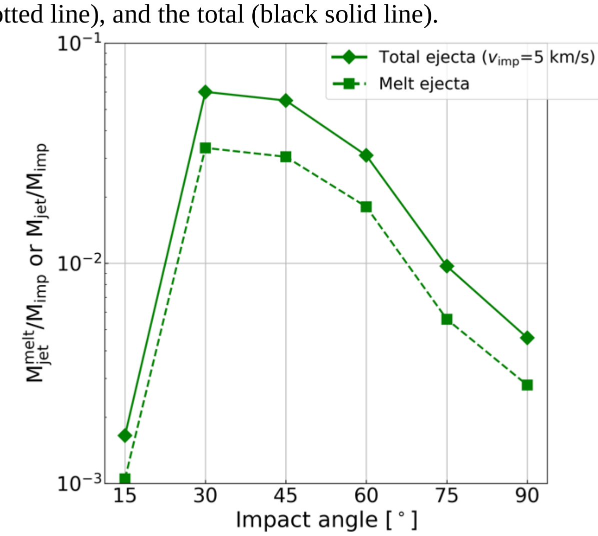

Figure 4: Same as Figure 3 but v_{imp} = 5 km/s. The dotted line represents the partially molten jetted ejecta, which exceeds the solidus temperature of dunite 1373K.