THE EFFECT OF IMPACT OBLIQUITY ON POROUS PLANETESIMAL COLLISIONS Thomas M. Davison[1,2], Fred J. Ciesla[1] and Gareth S. Collins[2]. [1]Department of the Geophysical Sciences, The University of Chicago, 5734 South Ellis Avenue, Chicago, IL 60637, U.S.A. [2]Impacts and Astromaterials Research Centre, Dept. of Earth Science and Engineering, Imperial College London, London, SW7 2AZ, United Kingdom. (E-mail: tdavison@uchicago.edu).

Introduction: Collisions between planetesimals were common events in the early Solar System. Recent work has suggested that impacts may provide a significant heat source as a complement to heating from short-lived radionuclide decay, especially in collisions between porous planetesimals [1]. Almost all impacts occur with oblique incidence. The most common impact angle is 45° from the horizontal, and the probability of an impact occurring at an angle < 70° from the horizontal is $\sim$ 90%. However, to date the effect of impact obliquity has not been accounted for in studies of collisional heating.

The effect of impact angle on crater shape is well documented: the crater size has been shown to scale with a dependence on $\sin(\theta)$ for impacts in the gravity regime, and with $\sin^2(\theta)$ in the strength regime [2]. However, Pierazzo (2000) [3] showed that the volume of material heated in an impact depends on the transient crater volume (which has a dependence on $\sim \sin^{1.3}(\theta)$ for planetary impacts [2,4]). In that pioneering study, the effects of porosity were not accounted for, and the results apply only for the case of an impact onto a planar target surface. The influence of target curvature on heating in oblique collisions has not previously been investigated.

Modeling: Here, we use the iSALE3D shock physics model [5,6] to investigate the effects of impact angle on heating in collisions between planetesimals, for a range of target curvatures and initial porosities. iSALE3D has previously been used to simulate oblique impacts into high strength materials [7] and for a range of gravity and strength dominated craters [6]. For this work, we have implemented the ε–α porous compaction model [8,9] in iSALE3D. We use Lagrangian tracer particles to record the peak shock pressure experienced by the material, and use the same method used in [1] to determine the mass of material heated during the impact.

Simulations were performed over a large parameter space. Parameters studied include the initial porosity (ϕ = 0 – 50%), the impact angle (θ = 90° – 15° measured from the horizontal tangent to the target surface) and target curvature (ratio of impactor-to-target radius, R_i/R_t = 0 – 0.2, where 0 is a planar target). The initial temperature of the material was 300 K, and the impact velocity was 4 km s^{-1}.

Results: The sum of the mass of all tracer particles that experienced a peak-shock pressure required to yield a range of post-shock temperatures was recorded for each simulation. In Figure 1, the results for three different target curvatures from a suite of simulations with an initial porosity of 50% are presented, showing the mass heated to 400 K, normalized by the heated mass in the normal incidence impact. At more oblique impact angles, the mass heated to a given temperature depends on the target curvature: the larger the impactor with respect to the target, the smaller the heated mass of material (relative to the heated mass in the normal incidence impact). This result is repeated in simulations with initial porosities of 0% and 20%. The amount of mass heated in the target is more dependent on the impact angle than the amount of mass heated in the projectile is — in all but the most oblique angles ($\theta > 30°$), the majority of the projectile is processed by the shock wave.

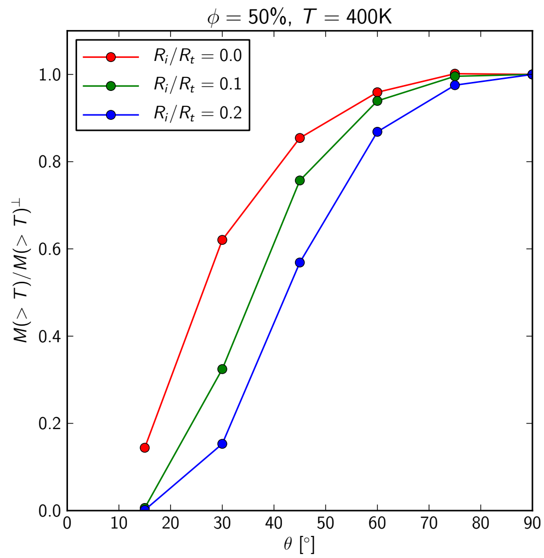

Figure 1: *The influence of impact angle and target curvature on impact heating, for collisions between planetesimals with an initial porosity of 50%. The ordinate axis shows the mass of material heated to 400 K, normalized by the mass heated to 400 K in the impact with a normal incidence angle. Impact angle is measured from the horizontal tangent to the target surface.*

Figure 2 plots each tracer particle that originated in the plane of impact (i.e. the plane that is is perpendicular to the target plane and includes the impact trajectory). Each particle is colored by its post-shock temperature, and plotted in its initial, pre-impact position (following the scheme of [3]). The top row of figures shows the heat distribution for impacts into a flat target plane (R_i/R_t = 0.0), and the bottom row shows impacts with

$R_i/R_t = 0.2$. Impact angles shown in Figure 2 are 90, 60 and 30°. For $\theta = 90°$, there is little difference between the two impacts. However, for $\theta = 60°$, a significant portion of the heated target is downrange of the impact point. In the collision into a curved surface, it is evident that the mass of material that is 'missing' between the horizontal tangent to the target plane at the impact point and the target surface is responsible for the differences in the amount of heating between the two collisions, as shown in Figure 1. This is also shown, to a greater extent, in the impacts with $\theta = 30°$.

Discussion: The target curvature has an influence on the amount of material heated to a given post-shock temperature. This effect is more pronounced for more oblique impact angles. Therefore, to determine the heated mass, one cannot simply use a scaling relation based on the impact angle alone. Recent work [10] used a measure of the mass of the projectile that would 'interact' with the target body ($M_{interact}$) to determine the effect of impact angle on the disruption criteria. However, for determining the heated mass of material, a more important factor is the available mass of the target, and how the shock wave interacts with and processes that mass. So, while it is important to account for $M_{interact}$ when calculating heated mass, that approach does not resolve the 'missing' mass between the target and curved surface. We will derive analytic relationships between the heated mass and the influential impact parameters (target curvature and impact angle) to account for both $M_{interact}$ and the available mass from the target. This will allow a quantitative comparison of oblique collisional heating with the major heat source for planetesimals, radionuclide decay.

Acknowledgements: We thank Boris Ivanov, Jay Melosh, Kai Wünnemann and Dirk Elbeshausen for their work in the development of iSALE3D. TMD and FJD were funded by NASA PGG grant NNX09AG13G. GSC was supported by NERC grant NE/E013589/1 and STFC grant ST/G002452/1

References: [1] Davison T.M., et al. (2010) *Icarus*, 208:468–481. [2] Gault D.E. and Wedekind J.A. (1978) *Proc. LPSC XI*, 3843–3875. [3] Pierazzo E. and Melosh H.J. (2000) *Icarus*, 145:252–261. [4] Schmidt R.M. and Housen K.R. (1987) *Int. J. Impact Eng.*, 5:543–560. [5] Amsden A.A. and Ruppel H.M. (1981) *Los Alamos Nat. Lab. Report* LA-8905 151p. [6] Elbeshausen D. et al. (2009) *Icarus*, 204:716–731. [7] Davison T.M., et al. (2011) *MAPS*, 46:1510–1524. [8] Wünnemann, K. et al. (2006) *Icarus* 180:514–527. [9] Collins et al. (2011) *Int. J. Impact Eng.* 38:434–439. [10] Leinhardt, Z.M. and Stewart, S. T. (2011) arXiv:1106.6084v2 [astro-ph.EP].

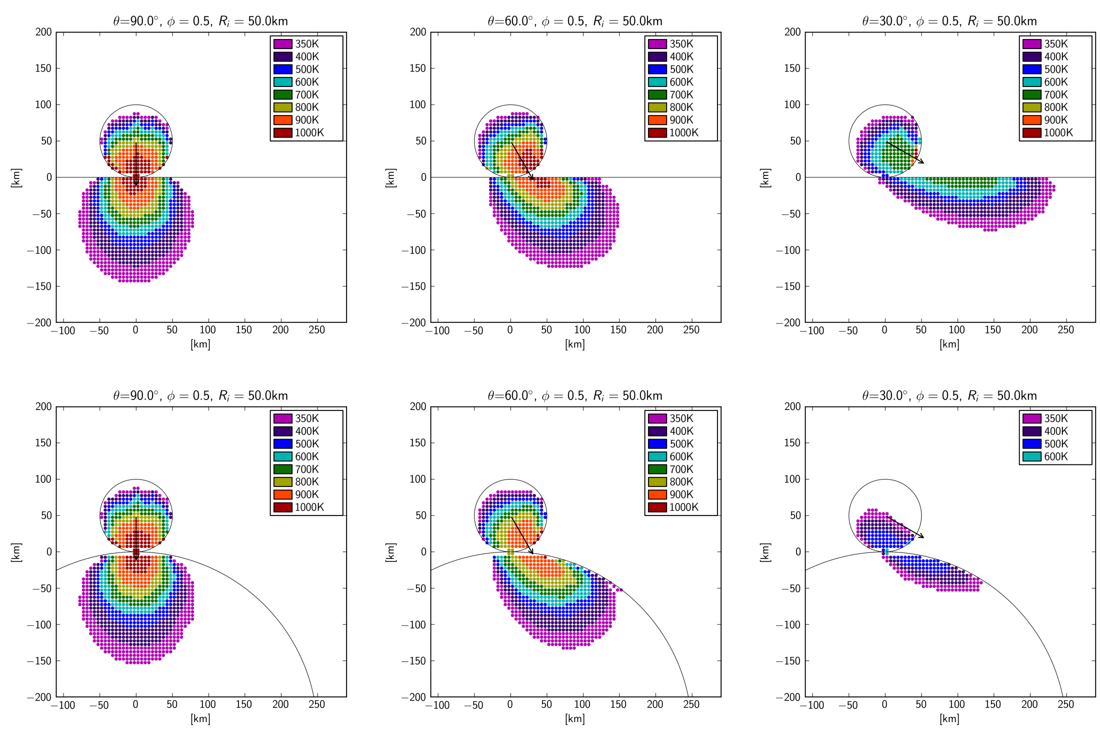

Figure 2: *Heat distribution in the plane of impact for a range of impact angles. Tracer particles are plotted at their initial, pre-impact position. Top row shows impacts into a flat target plane, bottom row shows impacts into a spherical target, with* $R_i/R_t = 0.2$.