DISTAL IMPACT EJECTA: MELT DROPLETS, IMPACT LAPILLI, AND TEKTITES. B. C. Johnson[1] and H. J. Melosh[2], [1]Purdue University, Department of Physics (Johns477@purdue.edu), [2]Purdue University, Department of Earth and Atmospheric Sciences.

Introduction: The size distribution and physical state of distal ejecta from large asteroid or comet impacts have long evaded prediction. We described the formation of globally-distributed vapor condensate spherules in a recent paper [1]. Here we advance a step further and describe the processes responsible for creating melt droplets, impact lapilli, and tektites, all of which arise from shock-melted, but not vaporized, material. We find that our order of magnitude estimates of the size of each product are in good agreement with observation. Our work also predicts that mm scale melt droplets should be found along with cm-mm scale impact lapilli and the more rare cm scale tektites. This prediction is consistent with the observation of melt droplets and impact lapilli found together in both the Chicxulub ejecta over 2000 km from the point of impact and the Sudbury ejecta found ~800 km from the point of impact [2, 3].

Results: Figure 1 shows schematically how the three ejecta products form in the ejecta curtain during initial ejection, not during re-entry and final emplacement. These ejecta products are not found in the global ejecta layer associated with the vapor plume or fireball. Instead, they are found in the more local non-global ejecta layer, consistent with being created in the ejecta curtain [2, 3].

We propose that turbulence within the ejecta curtain plays the essential role in creating impact lapilli and melt droplets. The low viscosity of melt and high ejection velocity of distal ejecta imply a high Reynolds number flow, which is inevitably accompanied by turbulence (Peter Goldreich Priv. Comm.). In a turbulent flow the fluctuating velocity and size of the largest turbulent eddies define the length scale and time scale of the flow. We find that the processes briefly described in Figs. 1a and 1b predict that the size of melt droplets and impact lapilli are dependent on the turbulent length scale and time scale.

Using iSALE to make high-resolution hydrocode simulations, we determined the properties of the turbulent shear flow within the ejecta curtain. In these simulations, we resolve material in the ejecta curtain that is ejected at velocities of ~5 km/s for an impact velocity of ~20 km/s. Contrary to popular belief, we find that there is no increase in shock level with increasing ejection velocity, a result qualitatively consistent with the Z-model picture, which predicts that materials span the entire range from unshocked to vapor at any ejection velocity. At typical Earth impact velocities, around 20 km/s, the ejecta curtain is composed completely of target material that has not been vaporized: There is no significant admixture of projectile material.

Melt Droplets: As shown in Fig 1b, small melt droplets form by the collisional breakup of larger droplets. After a lengthy derivation, which cannot be reproduced here, we obtain the following order of magnitude estimate of melt droplet size.

$$D_m \approx 0.9 \left(\frac{R_{imp}}{V_{ej}}\right)^{\frac{2}{3}}$$

where R_{imp} is the impactor diameter in km, V_{ej} is the ejection velocity in km/s, and D_m is the diameter of melt droplets in mm. This expression corresponds to mm scale droplets at ranges that are consistent with observations of distal ejecta.

Impact lapilli: The analytic expression we derived for the size of impact lapilli has a much stronger dependence on the impact velocity. We find that

$$D_{il} \propto V_{ej}^{-5.36\pm0.24}$$

this is very close to the estimate

$$D_v \propto V_{ej}^{-5.3\pm0.1}$$

for the size of particles implied by the radar-dark Venusian parabolas.[4] Additionally, we find using crater scaling relations that

$$D_{il} \propto R_c^{\frac{3}{3-\alpha}}$$

where Rc is the radius of the source crater and α is a scaling parameter that has a maximum value $\alpha = 3/4$. With this maximum value, we find

$$D_{il} \propto R_c^{1.33}$$

with a smaller exponent for smaller values of alpha. This is also in good agreement with the Venusian parabolas, as they correspond to

$$D_v \propto R_c^{1.03\pm0.33}$$

The expression derived by Schaller and Melosh [4] agrees well with the cm size impact lapilli found in Sudbury ejecta layer ~800 km from the point of impact in Minnesota and Canada [3]. Using parameters from the detailed hydrocode and assuming a 10% collection efficiency, we find our expression also corresponds to cm scale lapilli at this range. This evidence strongly suggest that the radar-dark Venusian parabolas are actually produced by impact lapilli in the normal ejecta curtain, contrary to previous suggestions that the particles were formed in the fireball.

Tektites: Lastly we have tektites, which form by initial fragmentation and subsequent collisions as shown in Fig 1a. The size we obtain for tektites is similar to that put forward by Melosh and Vickery [5]. After another lengthy derivation we are left with the following order of magnitude estimate for the size of tektites:

$$D_t \approx 4\left(\frac{R_{imp}}{V_{ej}}\right)^{\frac{2}{3}}$$

where R_{imp} is the impactor diameter in km, V_{ej} is the ejection velocity in km/s, and D_t is the tektite diameter in cm. This produces tektites that are generally cm sized, consistent with observations. We also conclude that molten tektites collide at low velocities, which is consistent with the presence of dumbbell shaped tektites. It is important to emphasize that our model suggest that tektites form from melted target material.

Conclusion: Three distinct populations of melt particles form in the ejecta curtain of large impacts in addition to unshocked broken fragments and spall plates. These populations comprise melt droplets, impact lapilli and tektites. The size each of these ejecta products has a unique dependence on the size of the impactor, as well as the ejection velocity and physical factors such as surface tension of the melt. The order of magnitude size estimates for the three ejecta products are consistent with the sizes observed in impact ejecta layers. The expression we derived for the size of impact lapilli has the same dependence on impactor size and ejection velocity as the particles that make up the Venusian parabolas. We cannot comment on the validity of our expressions for melt droplet size or tektite size as a function of impactor size and ejection velocity because there are no published observational estimates of this dependence. We hope that our work will stimulate research on the functional dependence of the size of the three ejecta products on impactor size as well as ejection velocity using geologic data. Only then can we validate our proposed mechanisms for the formation of these ejecta products.

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Fig 1. (right) is a schematic representation of the ejecta curtain and the processes happening within. The gray represents fragmented solid material. The dark orange represents melted material. The material in the ejecta curtain is textured to illustrate that it is made up of small particles of melted or solid material with void space or vapor making up a significant volume fraction. The circles with arrows represent the largest turbulent eddies that can form in the ejecta curtain. The large blocks on the underside of the ejecta curtain represent spallation fragments. **Frame a** describes the process that forms **tektites** at the top surface of the ejecta curtain. Tektites arise when shocked material reaches the liquid vapor coexistence curve and forms a boiling liquid that fragments into droplets whose size depends on the strain rate. These fragments undergo subsequent collisions, further decreasing their size. Those drops which have velocities directed away from the ejecta curtain will survive as tektites. Those that travel into the curtain will become melt droplets. **Frame b** shows the process that creates **melt droplets** in three different time steps. At t_1 , the two drops are moving with velocities that will cause them to collide. At t_2, the droplets collide. The Weber number, which depends on droplet size, collision velocity and surface tension, exceeds a critical value in this collision. The droplets may break up into several smaller droplets as shown at t_3. The collision velocity is highly dependent on the shear flow present in the curtain and the number density of droplets at a given time. **Frame c** shows the process that creates **impact lapilli**. Impact lapilli grow by accreting melt droplets and small shards of rock that are coated in melt by condensing vapor or collisions with melt droplets. The large lapilli collide with the smaller particle at a relative velocity **V** that is determined by the turbulent velocity.