MELT DROPLET FORMATION IN ENERGETIC IMPACTS; A. M. Vickery and H.J. Melosh, Lunar and Planetary Lab, The University of Arizona, Tucson, AZ 85721

It has long been known that impacts between rocky bodies at velocities exceeding about 15 km/s are capable of melting or vaporizing both the impacting object and a portion of the target (1). We have recently shown (2, 3) that geological materials initially shocked to high pressure approach the liquid-vapor phase boundary from the liquid side as they decompress, breaking up into an expanding spray of liquid droplets. We present a simple theory for estimating the sizes of these droplets as a function of impactor size and velocity. We show that these sizes are consistent with observations of microtektites and spherules found in the Cretaceous-Tertiary boundary layer, the Acraman impact structure, Archean beds in South Africa and the lunar regolith. The model may also apply to the formation of chondrules.

Although it has thus become clear that spherule formation is an important part of the impact cratering process, until now no reliable method has been found for estimating the spherules' size in a given impact event. Previous methods began with the assumption that the highest energy portion of the ejecta plume is completely vaporized (4) and that the condensates formed by homogeneous nucleation from the vapor phase. However, the studies of Montanari et al. (5) clearly indicate that the K/T spherules quenched from a liquid phase. Furthermore, our recent studies of the decompression of shocked dunite (2,3,6) and quartz using the ANEOS equation of state program (7) show that at common asteroidal impact velocities on Earth (~ 20 km/s) the shocked material follows a release path that intersects the liquid-vapor phase curve from the *liquid* side.

Shortly after an energetic impact event the impacting projectile and a roughly equal volume of the target are compressed to high pressure (8) and a density roughly twice the zero-pressure density. Highly shocked material begins in the liquid phase and expands to lower pressure and density. At this time the liquid undergoes an initial fragmentation into clumps whose diameter d_0 is determined (9) by the balance between surface tension σ and the local kinetic energy, $1/2\ m\ v^2$, where $v = \dot{\varepsilon}\, d_0$. This balance yields an initial clump size of $d_o = \left(40\sigma / \rho_\ell \dot{\varepsilon}^2\right)^{1/3}$, where ρ_ℓ is the liquid density at the moment of fragmentation and $\dot{\varepsilon}$ is the strain rate of the expanding melt. We estimate the strain rate as the ratio of the mean expansion velocity, v_{exp}, to the radius of the plume at the time of droplet formation, R_f. We assume that $R_f \approx L/2$, where L is the impactor diameter and $v_{exp} \approx v_i/2$ (10), where v_i is the impact velocity. For a 1 km diameter projectile striking at 20 km/s this yields $d_0 \approx 2$ cm, which is comfortably close to the size of tektites, supposing that some of the melt ejected from the crater escapes further fragmentation. This is more likely to occur in the lower speed, inner and slower, portion of the ejecta where most of the melt is derived from the target, consistent with the lack of siderophile element (projectile) contamination of tektites (11).

Following the initial fragmentation of the homogeneous melt, a second generation of droplet formation occurs in the more energetic part of the ejecta plume. Hydrocode computations we performed using the ANEOS parameters for dunite (3) show that vaporization begins when the mean density in the expanding melt falls to about half of its uncompressed density, or when the melt plume is about 1.6 times larger than its initial radius. The vapor mass fraction quickly reaches about 0.5, then begins to decline slowly as condensation onto existing droplets occurs. The ultimate droplet size is thus established in an environment in which both vapor and melt droplets are present. Assuming that the volume of vapor is much greater than the volume of melt, the droplet radius r is estimated from the balance of aerodynamic forces and surface tension. Our hydrocode calculations indicate that very rapidly reach an equilibrium size when the liquid fraction is at its minimum. This size is given by $r_{eq} = \sqrt{15\sigma C_D / 4\rho_d a}$, where C_D is the drag coefficient, ρ_d is the droplet density, and a is the acceleration of gas due to pressure gradients: The steady-state differential velocity between the drops and the gas is $\Delta v = \sqrt{5\sigma / \rho_g r_{eq}}$ and the time scale for droplet formation is $t_{eq} = [(1-\ell)\Delta v] / a$, where ρ_g is the gas density and ℓ is the liquid fraction. Using various approximations for the maximum (initial) pressure, the pressure gradient as a function of radius and time, a linear U_s-u_p EOS for quartz, and other constraints (10), we find that the minimum equilibrium droplet size for the high-energy portion of the ejecta plume is $r_{eq} \approx 0.11\sqrt{L} / v_i$ (SI units).

Assuming that the KT impact involved a ca. 10 km diameter asteroid with $v_i \cong 20$ km/sec, our model predicts $r_{eq} \cong 550$ µm, consistent with the observed spherule sizes in the KT boundary layer outside North America(12). The model also predicts $\Delta v \cong 1.3$ m/s, which is small compared to the mean expansion velocity of the plume, $v_{exp} \cong 10$ km/sec, and $t_{eq} \cong 0.05$ ms, which is small compared to the characteristic plume expansion time, $t_{exp} = R/v_i \cong 800$ ms. The smallest reported sizes of the late Eocene microtektites (13), microirghizites (14), and Ivory Coast microtektites (Glass, unpub. data) are consistent with the predictions of our model for reasonable combinations of L and vi. For the Archean Greenstone Belt microspherules (15) and the Australasian microtektites (16), however, the smallest sizes are inconsistent with this model, requiring extremely high impact velocities and/or impactor sizes unreasonably small for the masses of the strewn fields. Perhaps the spherules deposited in the near vicinity of impact craters are smaller than predicted by our formulation because the melt droplets were subjected to a further stage of breakup when the expanding melt and vapor plume from the impact came in contact with the ambient air, establishing a strong decelerating dP/dr gradient. Detailed numerical computations of the interaction of the projectile plume with the surrounding atmosphere should be able to answer these questions.

Our model may also apply to chondrule formation, although the application to this case is more speculative. The problem is that high relative velocities between colliding bodies is required to produce highly shocked melt plus vapor as in our model, and the ejected droplets would therefore be expected to encounter other bodies with similarly high velocities and be obliterated. This mechanism might work if chondrule formation took place while nebular gas concentration was high enough to slow the droplets by drag. The timing of events, however, may be rather delicate: condensation and accretion would have to have proceeded far enough to produce reasonably large planetesimals with high relative velocities to provide sources for the chondrules, but not so far that the nebular gas density was too low to slow down the ejected drops.

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