CONDITIONS FOR SINGLE AND MULTIMATERIAL JETS. G. H. Miller, *Shock Wave Lab, Department of the Geophysical Sciences, University of Chicago, 5734 South Ellis Avenue, Chicago IL 60637, USA, greg@geoleo.uchicago.edu*.

When materials collide obliquely a jet may form whose velocity and peak pressure-temperature conditions greatly exceed those that would occur in a plane impact with the same velocity. Jetting has been proposed as a mechanism for the formation of certain chondrules, the formation of tektites, and it has been suggested that jetting played a role in the formation of the moon in a giant impact and in the ejection of the SNC meteorites off the Martian surface.

An experimentally verified theory [1] exists for the symmetric collision of thin plates that describes the conditions under which jets form, and gives the mass and momentum fluxes of the jets. The entire theory does not apply to asymmetric collisions, thick plates, or spheres. Experiments involving asymmetric collisions of thin and thick plates give very poor agreement with thin plate theory [2]. It has been argued, based on thin plate theory, that jets formed when spheres collide ought to contain both impactor and target materials. Here a new theory is presented that argues for common conditions leading to single material jets. Preliminary experiments aimed at testing this theory are presented.

Theory. In a collision-centered reference frame a material stream must stagnate in order for it to reverse directions and jet. The thermodynamic state of the stagnation point can be constrained, but cannot be uniquely determined, knowing the eqn. of state (EOS) of the material and the impact conditions. In symmetric collisions the stagnation point lies on the interface between the impactor and target, and both impactor and target enter the jet in equal amounts. When symmetry is relaxed the stagnation point need not lie on the interface. If only one material stream stagnates then it will form the jet, and the other stream will enter only via entrainment.

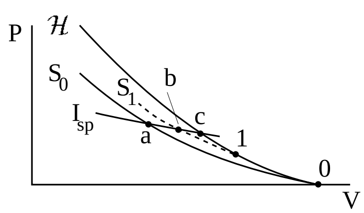


Figure 1: Thermodynamic model [3].

Fig. 1 shows the shock Hugoniot ($\mathcal{H}$) and principal adiabat (S_0) for a typical material. When the material stagnates, its enthalpy will be given by Bernoulli's law, $I_{sp} = U^2/2$. If the material stagnates but is unshocked, the stagnation point pressure is the intersection of I_{sp} with S_0 (pt. "a"). For a typical EOS this gives the highest possible stagnation point pressure, but as it is isentropic it has the lowest possible temperature. If the material stream passes through a shock, the thermodynamic state of the stagnation point must be the intersection of I_{sp} with a different adiabat, say S_1 (pt. "b"), and not the intersection of I_{sp} with $\mathcal{H}$ (pt. "c", *cf.* [4]). The greatest entropy state is the one with the largest single shock, which is the case when the shock is normal to the material stream. For any shock the material has a finite velocity as it emerges from the shock, and that kinetic energy must be converted to enthalpy along an adiabat. The stagnation point can lie anywhere in the range (P_b, P_a), depending on the strength of shock, which cannot be predicted *a priori*.

In an asymmetric collision, the ranges (P_a, P_b) for the target and (P_a, P_b) for the projectile may not overlap. This happens when the EsOS are widely different or when the angle between the materials is large. When the ranges do not overlap then either one material stagnates and jets, or both materials may stagnate separately. We have never seen more than one stagnation point in numerical computations of asymmetric collisions. Assuming a single stagnation point and steady state, thermodynamics alone can be used to predict circumstances under which jets will to be principally formed of a single component.

In asymmetric plane impacts, the stagnation pressure range in the projectile (Fig. 4) tends to be smaller than that of the target for purely geometric reasons. If the stagnation point falls in the smaller of the two possible non-overlapping ranges, which is what we find in our computations, then projectile-dominated jets would be expected. The extension of this logic to planetary applications is illustrated in Fig. 2. Terrigenous jets should occur in near-normal impacts, and meteoritic jets should occur in highly oblique impacts. Experiments to test this idea are underway.

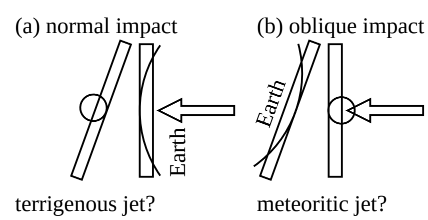


Figure 2: Meteoroid-planet impact analogy: (a) in normal impact meteoroid plays the role of target; (b) in oblique impact meteoroid plays the role of projectile.

In fact, according to the thermodynamic logic described here, conditions leading to single-material jets are far more common than those leading to multi-material jets. Fig. 3 shows a map of jetting conditions expected in the impact of a Cu thin plate against an inclined Sn thin plate. In regime (a) jetting does not occur. Jetting occurs in regimes (b,c) by the von Neumann condition, and in (d,e) under acoustic conditions where at most one material can have a steady-state shock. The jetting regimes are further subdivided according to whether or not the stagnation point pressure ranges of the target and projectile overlap. In regimes (b,d) the stagnation point pressure ranges of the target and projectile overlap, and it is possible that a single stagnation point on the material interface leads to a jet with substantial contributions from each material. In regimes (c,e) the ranges do not overlap, and if there is only one stagnation point it will involve only one material stream and tend to produce a single material jet.

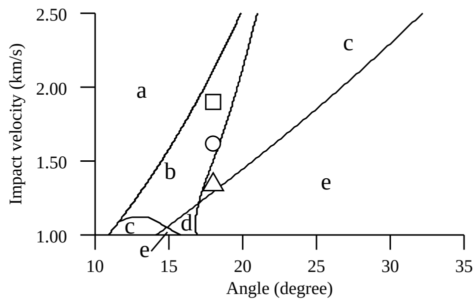
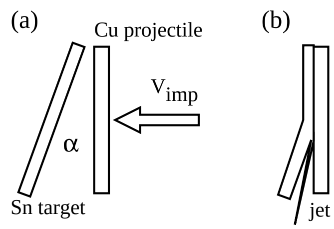


Figure 3: Jetting regimes for Cu projectile on Sn target. Symbols represent experiments analyzed in Fig. 5.

Figure 4: Experimental setup. (a) before and (b) after impact.



The theory described above strictly applies only to asymmetric thin plate impacts under conditions of steady state. In the experiments depicted in Fig. 4 steady state does not apply. This is because in a reference frame centered on the point of impact the material streams downstream of the point of impact have different velocities and are therefore subject to Kelvin-Helmholtz instabilities that cause the material interface to undulate chaotically [3]. In numerical hydrocode simulations of such experiments under conditions when only one material is expected to jet these interfacial instabilities can cause the other material to appear in the jet. This sometimes occurs because large rotational distortions at the point of contact lead to stagnation of the other material. Sometimes the undulating jet strikes the other material stream downstream of the impact point, ablating it and entraining it in the jet.

Experiment. We are conducting a series of experiments to test the predictions of Fig. 3. We impact 70mm-diam., 6.5mm-thick annealed oxygen-free Cu plates against 76 by 50 by 6.5mm Sn inclined plates. We record the jet using Al (shots 38,40) or steel (shot 39) witness plates precisely located 200mm (typ.) below the projectile centerline. The material pair Cu/Sn was chosen since regime (b) is significantly larger for this pair in the velocity range we can achieve (1, 2.5 km/s) than for any of over 700 other material pairs we modeled. Witness plates were used in lieu of polyethylene foam catch boxes (*cf.* [2]) since in our experience with the latter it is difficult to discriminate between material that enters the catch box in a jet and possibly shocked materials that were not jetted but enter on more complicated trajectories.

The witness plates record two distinct styles of secondary particle impact. First, an oblong scour pattern consisting of overlapping, symmetrically-radiating $\approx 20\mu$m-wide >10mm-long channels is present just downstream of the impact. This we attribute to scouring by jetted particles, the flow of which stagnates upon striking the witness plate, then radiates outward from the point of contact. The point of contact migrates downstream as the projectile-target impact progresses because of geometry, and may also vary because of interfacial instabilities. The overall pattern is large, ca. 100mm across, thus the angle of impact cannot be deduced with any certainty. Second, an array of well-formed circular impact craters, sub-mm to 5 mm diam., are found downstream of the scour pattern. The locations of these craters are inconsistent with their origin in jets. A hypothesis for their origin that is consistent with our observations is that they are due to fragments spalled off the downstream surface of the Sn target, resulting from occasional impingement of a chaotically-fluctuating jet against the target.

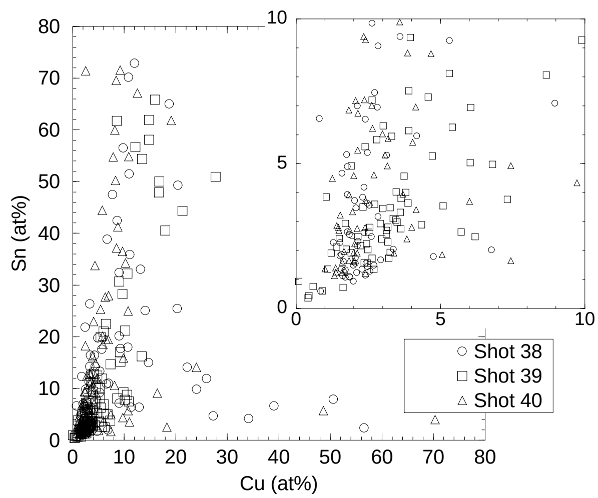


Figure 5: Witness plate analyses (by A. M. Davis).

The composition of jetted material plated on the surface of the witness plates (Fig. 5) is variable in all cases, with the majority of 1μm-spot analyses lying near Sn/Cu=5 (at%). Clearly in all cases both materials entered the jet, though the homogeneity (scarcity of Sn-only and Cu-only spots) may be an artifact of the witness plate collection method. Shot 40 (Fig. 3) is predicted to lie in a single-material region, but its witness plate record suggests this did not occur. This point lies near the multi/single material boundary, and the discrepancy might be due to errors in the EOS model for Sn. Experiments farther from this boundary are underway.

References. [1] Walsh J.M. *et al.* (1953) *J. Appl. Phys.* **24**, 349; Harlow F.H. and Pracht W.E. (1966) *Phys. Fluids* **9**, 1951. [2] Yang W. and Ahrens T.J. (1995) *Icarus* **116**, 269. [3] Puckett E.G. and Miller G.H. (1997) *Proc. 20th ISSW*, in press. [4] Kieffer S.W. (1977) in *Impact and Explosion Cratering*, ed. Roddy D.J. *et al.*, 751.