IMPACT JETTING: COMPARISON BETWEEN SPECTROSCOPIC OBSERVATIONS AND A STANDARD THEORY.

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Summary: Impact jetting has been proposed as a key process to solve many problems in planetary geology. An experimentally verified semi-analytical standard jetting theory has been used for such planetary applications. Previous experimental verifications, however, do not cover energy partitioning during the jetting process. Using a newly developed spectroscopic method, we observe jetting temperature to constrain the energy partitioning processes. Obtained jetting temperatures are compared with the standard jetting theory. Calculation results indicate that jets created by 4-6km/s impacts may attain the observed high temperatures (4-9000K). The theory, however, does not readily explain the impact-angle effect. Additional heating mechanisms other than shock heating may be necessary to understand the angle effect on jetting temperature.

Introduction: Jetting phenomena have been described for a variety of impact conditions [e.g., 1,2,3] and also have attracted attention in planetary science as a possible formation mechanism of chondrules and impact glasses [4,5], planetary accretion [6], and the origin of the Moon by a giant impact [7]. Although considerable research has been done for jets created by colliding symmetric thin plates, few quantitative observations have actually been made for jetting due to blunt-body collisions, which characterize naturally occurring impacts at planetary scales. In particular, no quantitative observations have been made for energy partitioning during jetting due to blunt-body collisions. Consequently, a classical model of symmetric thin-flat-plate collision [8,9] has been often applied to assess jetting phenomena due to blunt-body collisions [5,6,7,9].

Although such applications probably serve for first-order estimates, there is no experimental verification. In fact, even a flat-plate collision departs significantly from predictions of the classical jet model when the colliding plates are thick [10]. Thus jetting due to blunt-body collisions may depart greatly from predictions by the classical thin-flat-plate model.

Our previous experiments revealed that jetting temperature of quartz impacts into dolomite targets is largely controlled by the vertical component of impact velocity [11]. It was, however, uncertain if this result is unique to this particular combination of projectile and target materials. Physical significance of this result was also unclear since there was no theoretical comparison. In this study, we observe jetting due to a different material of projectiles and perform theoretical calculations for jetting.

Experiments and Results: Impact experiments were conducted at NASA Ames Vertical Gun Range (AVGR). Spherical copper projectiles were launched into solid polycrystalline dolomite targets at variable velocities (4.7-5.8km/s) and angles (15°-90°, measured from the horizontal). The spectroscopic measurement system used here is described elsewhere [11].

Since strong emission lines of both Ca and Cu atoms were observed in all the impacts, the temperatures of jets from both targets and projectiles could be measured. Unlike quartz impacts [11], copper impacts do not show good correlation between jetting temperature and the vertical component of impact velocity. Fig. 1 shows both jetting temperatures and mass ratio as a function of impact angle. The temperature of target-derived jets does not show clear increase or decrease over the experimented range of impact angles (Fig. 1a). The jet temperature of projectile component, however, shows slight increase from 15° to 75° and decrease from 75° to 90° although there is significant scatter (Fig. 1b). Fig. 1 also shows that copper temperature is roughly 1500K higher than that of calcium. In fact, there is significant correlation between the temperatures of the two components of the jets. Fig. 1c clearly shows that target mass ratio in impact jetting monotonically increases with impact angle.

Comparison with a Standard Theory: The amount of shock heating was calculated using both the analytical model for asymmetric collision of thin flat plates by *Walsh et al.* [8] and the method to estimate the maximum shock heating by *Kieffer* [9]. Although some of the model assumptions are not satisfied by the experimental conditions (e.g., the colliding objects must be thin plates; the shock front needs to be steady state), the asymmetric model includes the effects of contrasts in impedance and effective impact velocity between a projectile and a target, which a symmetric model does not consider [12].

Fig. 2 shows the maximum shock heating during jetting as a function of both impact velocity and angle. Note that the shock heating of the target is calculated with the Hugoniot data of calcite (data for dolomite are not available). Shock heating of the target-component jet is always more than twice that of plane-normal shock for a given impact velocity. Fig. 2 also shows that even jetting requires about 4 km/s to achieve the heat of vaporization (~11MJ/kg) of carbonate. Similar calculations indicate that quartz impacts require a higher impact velocity to achieve full vaporization of carbonate. This is consistent with the observation that the intensities of calcium emission are very faint for quartz impacts at velocities less than 5 km/s [11].

The calculated dependence of shock heating on impact angle, however, departs largely from observations. The model predicts that shock heating of the projectile-derived jet is very small at low impact angles (Fig. 2).

Copper projectile should not vaporize at low angles. However, relatively high temperature of vaporized copper jet is observed at low impact angles (Fig. 1b).

Discussion: How does projectile-derived jetting achieve such a large internal energy at low impact angles? The above calculations based on the classical jetting theory have several simplifying assumptions. Breakdown of these assumptions potentially accounts for the discrepancy between the theory and the observations. First, the shock pressure on the shock fronts is not equal to that at the stagnation point [9,13]. Second, the flow around a collision may not be in a steady state [13,14,15]. Third, the flow is not inviscid.

Fluid dynamical considerations, however, indicate that the gap between stagnation pressure and peak shock pressure widens the discrepancy, particularly at low impact angles [12]. The effects of non-steady-state flow also do not readily account for the discrepancy, although it deserves further considerations [12]. The breakdown of the assumption of inviscid flow, however, may explain the discrepancy. At lower impact angles, viscous shear heating may increase the temperature of the jet more effectively and compensate for the lower shock heating. More specifically, the velocity difference along the material interface between target and projectile is greater at lower impact angles. If the viscous shear process enhances coupling between the projectile and the target along their interface, it may account for temperature correlation between jets from both projectile and target. Previous experiments indicate that shear heating also appears to enhance impact vaporization at later stages [16]

Conclusion: The results of the comparison between spectroscopic observations and theoretical calculations strongly suggest that the current standard jetting theory does not describe accurately energy partitioning processes during jetting due to blunt-body impacts. This demonstrates need for further investigations on the factors discussed above, such as non-steady-state flow and shear heating during impact jetting.

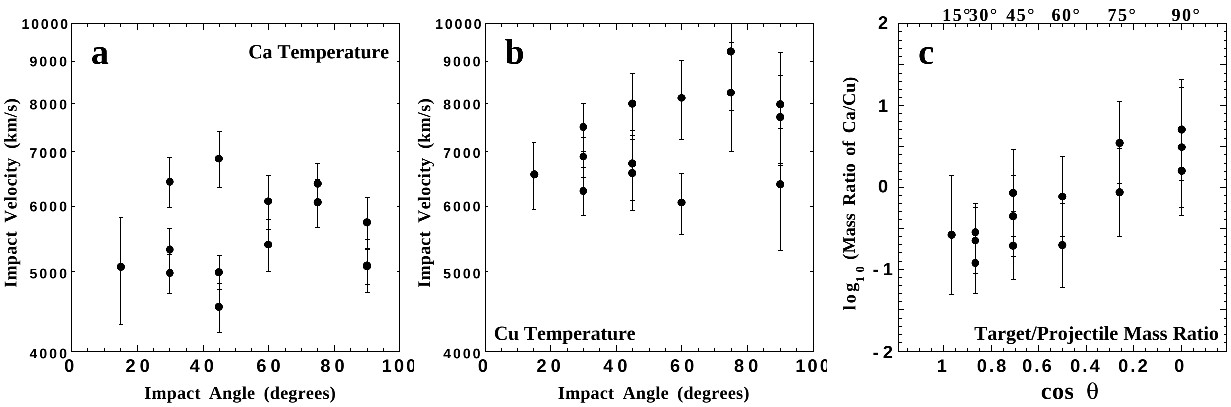

Figure 1. Temperatures of (a) target-derived jet and (b) projectile-derived jet and (c) target-projectile mass ratio in jet. Impact velocities are 5.35±0.25km/s. Error bars indicate 1σ-confidence levels.

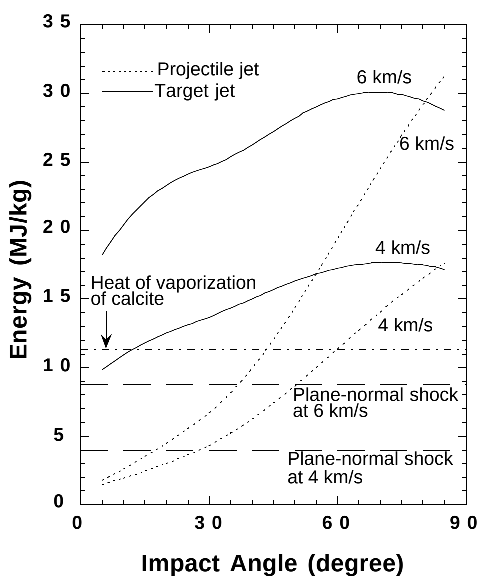

Figure 2. Theoretical prediction of maximum internal energy of jetting due to copper spheres impacting into carbonate targets.

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