JETTING AND THE ORIGIN OF TEKTITES

A. M. Vickery, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721

The origin of tektites was a hotly debated subject for many years. Tektite strewn fields extend hundreds to thousands of kilometers across the earth's surface, and the problem of propelling molten material through the earth's atmosphere without disrupted it into a fine mist (1) led a number of investigators to propose an extraterrestrial origin for tektites (2,3). A large amount of geochemical evidence, however, strongly suggests that tektites were produced by the (presumable impact-induced) melting of terrestrial sediments (4), and most people now believe that the terrestrial origin of tektites has been proved beyond a reasonable doubt (e.g.5). The most widely-cited mechanism for tektite production is jetting during the early stages of impact, although the only previous dynamic study of jetting with regard to this problem (1) concluded that the jet would break up into a fine mist. The problem is compounded by the evidence from the primary shapes and ablation characteristics of the australites, which stongly suggests that they solidified as spheres (implying extremely low differential pressures) and subsequently entered the earth's atmosphere from above (2).

In this study, the theory of jetting due to the collision of thin plates (6-10) was extended to the case of the impact of a sphere at arbitrary impact speed U and angle α from the vertical onto a half-space (c.f. 11).The tangent to the sphere at the locus of intersection is assumed to correspond to the upper plate and the surface of the target, to the lower plate. There are two frames of reference that are typically used in jetting studies: In the standard frame, the two plates converge with equal and opposite velocities v_p perpendicular to the plates, the jet is directed along the bisector of the angle (2θ) between the plates, and the locus of intersection P moves forward as the plates converge. Jetting will only occur if $\theta > \theta_{crit}$ (7-9), where θ_{crit} is a function of v_p. The jet velocity is

$$v_j = |v_p| \left(\frac{1 + f\cos\,\theta}{\sin\,\theta} \right)$$

where f~1 from experiments. In the collision frame, the material in the plates moves with a velocity $v_o = v_p \cot\theta$ along the plates into the now stationary intersection P. The jet velocity in this frame $v_1 = fv_o \sim v_o$, combined with information on the jet width (10) essentially gives the rate at which material is fed into the jet. In addition to these to frames of reference, the current problem requires the target frame, in which the target half-space is stationary, and the convergence velocity depends on both the impact velocity and the current geometry (the degree of penetration of the sphere into the half-space). The jet velocity in this frame is the ejection velocity relative to a stationary target and is initially unknown. A vector v_t is derived to translate from the target frame to the standard frame, which requires the assumption of differential slip within the jet (asymmetric jetting (7)). The translation vector is then applied in reverse to v_j to get the jet velocity in the target frame v_j'; v_j' is not directed along the bisector of the angles between the converging surfaces nor is it directly radial from the center of impact. Similarly, the relation between the target and collision frames permits an estimate of the mass flux into the jet. Because jetting is asymmetric, the projectile and target contribute different amounts of mass to the jet.

The pressure at the stagnation point P was estimated using the method of (12) using a piece-wise linear shock velocity-particle velocity equation of state for olivine. It was assumed that release from pressures of 7.3×10^{10} Pa, 1.0×10^{11}Pa, and 5.0×10^{11} Pa would result in melting, incipient vaporization, and complete vaporization, respectively. A computer code was developed that calculates the mass ejected, its phase, the ejection speed, elevation and azimuthal ejection angles, and projectile fraction within the jet as functions of time. Mass averages of these quantities were calculated for each timestep and for the entire duration of jetting.

Because jetting is a hydrodynamic process, the mass jetted scales rigorously with the mass of the impactor; thus all the calculations involve an impactor with radius 100 m (density 3200 kg/m^3). Impact velocities of 15, 20, and 25 km/s and impact angles ranging from 0° (vertical) to 75° in 15° increments were used.

RESULTS: (1) Overall Mass Averages: The total mass jetted increases with impact velocity (U_i) and decreases (slightly) with increasing obliquity of impact for $\alpha = 0 - 60°$, then increases for $\alpha = 75°$. The increase is more pronounced at lower U_i. In all cases, vapor dominates the jet, most strongly at higher U_i and low α. Overall jet velocity increases with U_i and decreases with increasing α. Again, vapor strongly dominates axcept at $\alpha = 75°$. The mean elevation angle of the jet increases with α from ~7° at $\alpha = 0°$ to 20-25° at $\alpha = 75°$, with melt generally ejected at higher angles than the vapor. The projectile fraction in the jet (Fp) varies between 0.40 and 0.50 and increases slightly with α; Fp in the melt ranges from ~0.2 at high U_i and low α to > 0.5 at high α. Jetting is azimuthally symmetric for $\alpha = 0°$, and becomes increasingly focussed downrange with increasing α. In general, the melt fraction is more concentrated downrange than the vapor fraction.
(2) Time Dependence: The mass flux is maximum at the onset of jetting and declines more rapidly for more nearly vertical impacts. Except for $\alpha = 0°$, the mass flux either levels off, or goes to a local minimum and then increases slightly before a final decline; this effect is less pronounced at higher impact velocities and smaller α. Similarly the jet velocity is greatest at the onset of jetting; the lower α, the greater the initial velocity and the more rapid its decline. Vapor is ejected first and at the highest velocities. At $U_i = 15$ km/s, the elevation angle is initially < 5° for all α and increases with time and α to a maximum of ~35° at $\alpha = 75°$. The azimuthal extent of jetting decreases with increasing obliquity and with time at a given obliquity.

APLICATION TO TEKTITE FORMATION: Although these results are preliminary, they suggest that for reasonable asteroidal impact velocities, a very high velocity vapor jet is produced that, as it expands adiabatically, can engulf and accelerate a significant volume of ambient atmosphere away from the impact site. The melt fraction of the jet is thus ejected into a much rarified ambient atmosphere, suppressing break-up of the molten jet. Whether and under what conditions this can explain the extraordinary extent of the Australasian and North American strewn fields and particular characteristics of the australites is beyond the scope of this study.

REFERENCES: (1) E. Adams (1965) *N. Jb. Miner. Mh.* **9**, 332. (2) D. R. Chapman and H. K. Larson (1963) *J. Geophys. Res.* **68**, 4305. (3) J. A. O'Keefe (1976) Tektites and Their Origin, Elsevier, N.Y. (4) S. R. Taylor (1973) *Earth Sci. Rev.* **9**, 101. (5) R. Brett and M. Sato (1984) *Geochim. Cosmochim. Acta* **48**, 111. (6) G. Birkhoff et al. (1948) *J. Appl. Phys.* **19**, 563. (7) J. M. Walsh et al. (1953) *J. Appl. Phys.* **24**, 349. (8) W. A. Allen et al. (1959) *Phys. Fluids* **2**, 329. (9) L. V. Alt'schuler et al. (1962) *Sov. Phys. JETP* **14**, 986. (10) F. H. Harlow and W. E. Pracht (1966) *Phys. Fluids* **9**, 1951. (11) H. J. Melosh and C. P. Sonnet (1986) in: Origin of the Moon (Hartmann, Philips, and Taylor, eds.) L.P.I., Houston. (12) S. W. Kieffer (1977) in: Impact and Explosion Cratering (Roddy, Merrill, and Pepin, eds.) Pergamon, N.Y.