WHEN WORLDS COLLIDE: JETTED VAPOR PLUMES AND THE MOON'S ORIGIN. H.J. Melosh, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

Sixteen years after the first manned lunar landing, the moon's origin, one of the ostensible scientific goals of the Apollo missions, is still in doubt. Of the three major hypotheses, fission, capture, and co-accretion, none satisfies the observational data without recourse to special pleading or deus ex machina. Recently, however, Cameron and Ward (1) suggested that a collision between the proto-earth and a Mars-size proto-planet might have both imparted the present angular momentum to the earth-moon system, and have injected silicate material into orbit. This material would subsequently condense into the moon.

The Cameron-Ward hypothesis received additional study at the recent (Oct. 13-16, 1984) conference on the Origin of the Moon at Kona, Hawaii. Stevenson (2) emphasized that the impact ejection of vapor mixed with solid debris could provide the necessary "second burn" to inject material into Keplerian orbits that do not re-impact the earth's surface. Viscous dissipation within the cloud of orbiting debris would rapidly cause some material to move outside the radius of synchronous rotation and there condense into a proto-moon that would recede from the earth under the influence of tidal dissipation.

Neither Cameron and Ward (1), Cameron (3), or Stevenson (2) examined the mechanical conditions of a very large impact. Cameron and Ward (1) suppose that the ejected material is predominantly composed of the projectile, whereas Ringwood (4) supposes that the moon accreted primarily from vaporized earth mantle material plus a small iron core component.

This abstract describes an approximate computation of the collision of two comparably-sized planetary objects, concentrating on the high-speed ejecta. A surprisingly large amount of material can be ejected as high-speed, hot vapor (up to 40% of the mass of the impacting object). Roughly half of this vapor is derived from the projectile, and half comes from the target (the proto-earth). The mass of material ejected is a strongly peaked function of the impact parameter b (see Fig. 1) and the ratio of radii of the two colliding objects (see Fig. 2). The probability of a collision at just the right impact parameter is thus low, making it plausible that large moons are rare. The large object which struck the earth fortuitously had an impact parameter near the peak in the ejected mass curve. Large objects which may have struck Mercury, Venus, or Mars did not have impact parameters near the peak and so these planets lack large moons.

The fastest, most highly shocked material ejected by an impact is thrown out during the contact stage by the process of jetting (see, e.g., 5 for a review of impact mechanics). An insignificant quantity of lightly shocked material ($\sim 10^{-4}$ projectile mass) is ejected at earth circular orbit velocity (7 km/sec) by the process of spallation (6). The bulk of the mass ejected is thrown out at less than 10% of the impact velocity, as demonstrated by direct studies of secondary craters and ejecta blankets around large crater (7). This latter component, the material forming the classic "ejecta curtain", is thus of no importance to the putative impact origin of the moon.

The only high speed ejecta that might contribute significantly to earth-orbiting debris is thus material jetted from the moving interface between the target and projectile during the earliest phases of the collision (although in very oblique collisions a portion of the projectile may ricochet, and could conceiveably add to the jetted material, the ricocheted projectile would not be vaporized and could not, by itself, acquire the necessary "second burn" non-Keplerian acceleration).

Gault et al (8) state that "only a few percent" of a projectile mass is jetted in the liquid (at 6 km/sec impact speed) or vapor states. However, Gault's et al's experiments were on spherical projectiles incident upon plane targets with only moderate (or no) obliquity. Although no experiments have yet been performed on jetting during the impact of equal or subequal spheres, there is a broad base of theoretical understanding of jetting (9,10,11,12,13) that can be used to make theoretical estimates of the mass of material jetted from the collision between a Mars-size proto-planet and the proto-earth.

The results of these estimates are shown in Fig. 2. They take into account both the complex and changing geometry during the collision and the physics of jetting. The principal approximation made in these calculations is that the width of the jet under the transient conditions of the collision is nearly the same as the width of the steady state jet computed theoretically. The validity of this assumption has not yet been tested.

The computations also show that the mass-averaged angle of ejection of the vapor is about 25° above the horizon of the target planet, and that most material is jetted within $\pm 25^{\circ}$ of the impactor's flight direction for impact parameters greater than roughly half the target planet's radius. The jetted gas forms a relatively narrow down-range fan or plume. The mass-averaged ejection velocity is only slightly less than the impact velocity V_0. Thus, if any large fraction of this material is to orbit around the earth, the impact velocity must be close to the proto-earth's escape velocity, 11 km/sec. This result contradicts Stevenson's (2) speculation that a high impact velocity is necessary (and thus that the impactor's orbit must be very eccentric or inclined). The jetted material is almost completely vaporized, even at impact speeds of 11 km/sec, because of the well-known (12) pressure multiplication during jetting.

The results of these computations make it seem likely that massive, high-speed vapor plumes form during the oblique collision of large planets. The plume's total mass is a strong function of impact parameter. At the peaks, which occur near impact parameter $b = (r_1 - r_2)$, the plume's mass approaches 40-50% of the impacting projectile's mass. The material of the plume is contributed roughly equally by the projectile and target. Plume material is derived from depths no greater than one-half the projectile's radius. If the projectile has a core smaller than this, core material will not be ejected in the plume. The plume is ejected at speeds only slightly lower than the impact velocity.

This vapor plume expands hydrodynamically after its ejection. Because the plume's free hydrodynamic divergence angle exceeds the angle between the target and projectile's surface, this expansion is confined by the moving surfaces, and is thus highly complex. It has not yet proved possible to compute this hydrodynamic flow. Nevertheless, under the right conditions, the computations cited above show that jetting is capable of ejecting a massive plume of vaporized material from the earth at oribtal speeds. It thus lends a higher degree of probability to the hypothesis that the moon originated from the collision between the proto-earth and a very large object.

Fig. 1 Geometry of a collision between the proto-earth and another proto-planet.

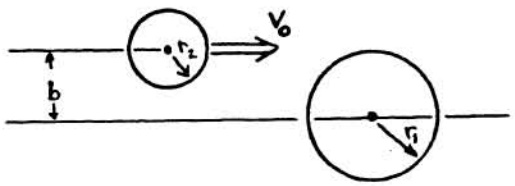
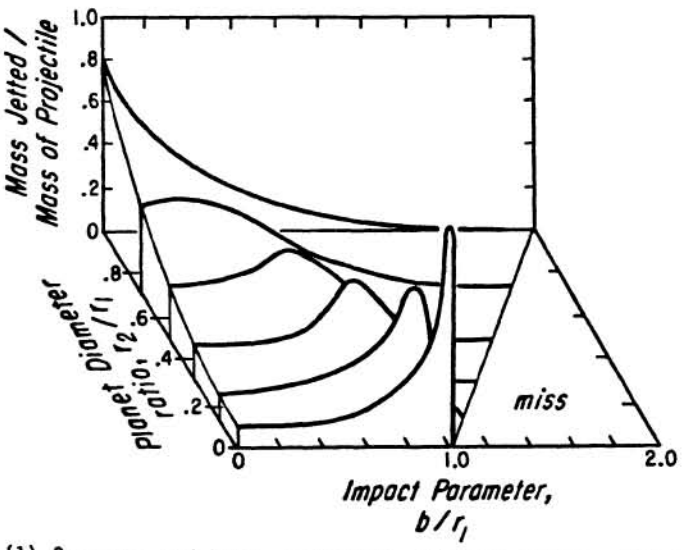


Fig. 2 Total jetted mass in units of the small planet (r_2) mass as a function of the radius ratio r_2/r_1 and normalized impact parameter b/r_1. Note that the jetted mass shows prominent peaks as a function of impact parameter.



REFERENCES. (1) Cameron and Ward, LPSC VII, 120-122 (1976). (2) Stevenson, Abstr. Conf. Origin of Moon LPI #540, 60 (1984). (3) Cameron, ibid, 58 (1984). (4) Ringwood, ibid, 46 (1984). (5) Melosh, Ann Rev. Earth, Planet Sic. 8, 65-94 (1980). (6) Melosh, Geology, in press (1985). (7) Vickery, LPSC XV, 880-881 (1984). (8) Gault et al, NASA Tech. Note D-1767 (1963). (10) Walsh et al, J. Appl. Phys. 24, 349-359 (1953). (11) Harlow and Pracht, Phys. of Fluids 9, 1951-1959 (1966). (12) Kieffer, Impact and Explosion Cratering, 751-769 (1977). (13) Kieffer, Science 189, 333-340 (1975).