OBlique Impacts: Ejecta Mass and Velocity Distributions; S. J. Weidenschilling and D. R. Davis, Planetary Science Institute, Tucson, Arizona

In the solar system, normal impacts are the exception, and oblique impacts the rule. The mean angle of impact on a spherical planet is $45^\circ$ from the vertical. Despite this fact, there are very few data on oblique impacts. The principal published study by Gauld and Wedekind (1978) was concerned with effects on crater size and morphology, and qualitative descriptions of ejecta patterns. For several years we have been carrying out a program of oblique impacts at the Ames Vertical Gun Range. One goal of our study is to determine whether the ejecta mass/velocity distribution, averaged over all impact angles and azimuths, varies significantly from that derived from normal impacts. Also, oblique impacts transfer angular momentum to target bodies. The theory of Harris (1979) for evolution of rotation rates of planetesimals and asteroids contains arbitrary parameters to account for forward-scattered and escaping ejecta. Experimental data are needed to make predictions based on this theory and to interpret asteroid rotation rates.

In our experiments, the target area is surrounded by cardboard and/or aluminum ejecta catchers forming segments of concentric rings, extending from 10 cm to 100 cm from the impact point, and divided azimuthally into $30^\circ$ segments. The rings have raised outer rims to prevent ejecta from rolling or bouncing beyond their landing points. After each shot, ejecta from corresponding segments on either side is combined and weighed (to first order, this removes the effect of left-right errors in aiming). Each shot yields up to 36 measurements of ejecta vs. radius and azimuth. The Ames test chamber geometry allows impact angles at $15^\circ$ intervals from $0^\circ$ to $75^\circ$ zenith angle, $\theta$. The velocity range covered is $0.7$ to $5.5$ km/sec. Projectiles are Pyrex, Al, and steel; the target material is quartz sand in all cases. All shots are filmed by a camera looking crossrange near the level of the target surface. The angle of the ejecta cone in the uprange and downrange directions can be measured, but individual particles or clumps of ejecta are not resolved. By assuming a launch elevation angle $\lambda$, ejecta velocity can be derived as a function of distance, $R$. Following Hartmann (1985) we assume $V_{ej} = (g(R-R_{rim})/2\sin \lambda \cos \lambda)^{1/2}$, where $R_{rim}$ is the crater radius. Launch angles generally appear steeper in the uprange direction. Fortunately, $V_{ej}$ is nearly independent of $\lambda$ in the vicinity of $\lambda = 45^\circ$. The cumulative mass distribution of the recovered ejecta can generally be extrapolated consistently back to $R_{rim}$.

We plot the log of cumulative mass recovered vs. distance to the inner boundary of each ring, for each of six divisions in azimuth, $\gamma$. For a Pyrex projectile with $v = 2$ km/sec and $75^\circ$ zenith angle, ($\gamma \equiv 0$ in the downrange direction) the uprange segments ($\gamma > 120^\circ$) show depletion in mass by about a factor of two relative to the mean, but the same slope of $M$ vs. $R$ for all azimuths. Other shots at different velocities and impact angles show the same behavior; while the azimuthal distribution of mass varies, the slopes of $M$ vs. $R$ or $V_{ej}$ are independent of $\gamma$. The slope of the distribution also appears to be independent of the impact angle and velocity over the range of conditions tested to date. These data strongly support the use of a single functional relationship to describe ejecta mass vs. velocity for both normal and oblique impacts.

The measured slope of log $M$ (cumulative) vs. log $V_{ej} = 1.4$; this implies a relatively larger amount of kinetic energy in the higher-velocity ejecta.
If this trend continued to $V_\text{j} \geq 10$ m/sec, the ejecta kinetic energy would exceed that of the impact. Clearly, the slope of the distribution must steepen and/or reach a cutoff at higher velocities. The data do show a steepening trend at $V_\text{j} \geq 2$ m/sec, partly due to failure to measure ejecta that landed beyond the outermost collectors, but extrapolating $M$ vs. $R$ at constant slope accounts for only about half of the discrepancy. There appears to be a real drop in the amount of ejecta at velocities above a few m/sec. Such a trend also appears in Hartmann's data for normal impacts into powdery material. Unfortunately, the size of the AVGR test chamber limits investigation of this phenomenon. Any ejecta with $V \geq 3$ m/sec will strike the side walls of the chamber before reaching the surface of the collector. More complex methods of ejecta collection and velocity measurement are necessary to measure this material. At present, we cannot exclude the possibility that the distribution of ejecta at higher velocities may depend on impact angle.

In highly oblique impacts, ($\theta \geq 60^\circ$), a small amount of very high-speed material may be ejected downrange on very low trajectories, nearly tangent to the target surface. Gault and Wedekind (1978) called this phenomenon "ricochet," although it is not clear whether the high-speed material is mainly derived from the projectile or target. We find that the amount of high-speed material, or at least the amount of damage to our downrange ejecta collectors, increases significantly with impact speed in the range 1-5 km/sec. The phenomenon depends on projectile material, and seems to occur at steeper incidence angles (smaller $\theta$) for Pyrex projectiles than for aluminum or steel. Additional shots at angle increments less than $15^\circ$ are needed to define the "ricochet" regime.

The importance of "ricochet" is that the high-speed material, although low in mass, may carry a significant amount of the total ejecta momentum. We estimate the total downrange component by plotting cumulative values of $(\text{mass} \times V_\text{j} \times \cos \lambda \times \cos \gamma)$. As for the separate mass and velocity distributions, the momentum distribution is linear on a log-log plot, and can be extrapolated back to the crater rim consistently. The net horizontal momentum due to the downrange asymmetry of the recovered ejecta blanket is $\leq 5\%$ of the projectile's transverse momentum. Thus, only a small amount of high-speed "ricochet" material may carry more total momentum than the low-speed ejecta.

The azimuthal distribution of ejecta blankets appears to depend on the angle of impact and the projectile material. As the zenith angle $\theta$ increases, the fraction of ejecta concentrated in the downrange direction increases through $\theta = 45^\circ$, then decreases, with more ejecta in the cross-range direction (as noted qualitatively by Gault and Wedekind). This behavior is less apparent for strong and/or ductile projectiles of steel or aluminum than for Pyrex. At $\theta = 45^\circ$ (corresponding to an "average" impact on a spherical body) the downrange ejecta blanket is twice as thick as that in the uprange direction. Such asymmetry has not been recognized in photogeological studies of planetary cratering. This may be due to problems in scaling to larger impacts, but we suspect that the asymmetry would be less for higher impact velocities. This idea remains to be tested, but if correct, it might be useful in discriminating (in a statistical sense) between low-velocity (planetocentric) and high-velocity (heliocentric) cratering populations on planetary satellites.