FORMING THE SOUTH-POLE AITKEN BASIN: THE EXTREME GAMES

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Abstract: The large backside basin on the Moon (South Pole-Aitken, SPA) was first recognized in the early 70s (1, 2) but has been more clearly defined only recently from Galileo (3) and Clementine missions (4). It presents a serious challenge to our understanding of the impact process for several reasons. First, nominal scaling relations would predict that such a collision should have disrupted the entire Moon. Second, gravity and topographic data indicate that in spite of its enormous size, it apparently did not result in uplift of the lunar mantle as in other major basin-forming impacts (4). Third, a well-defined series of massifs has survived even though most of the structure has been destroyed (1). And fourth, the farside lunar highlands seem to be thickened at one end of the long axis (4). It is proposed that such enigmas can be resolved for a low-velocity and low-angle impact by an object whose radius (r) becomes a significant fraction (>10%) of the impactee radius (R). At such extremes, fate of the impactor following first contact with the surface largely controls the total energy ultimately partitioned to the cratering process. In contrast with other large lunar basin-forming impacts (5), much of the SPA impactor debris failed to strike the surface downrange. Nevertheless, it is speculated that much of this debris may have contributed to the narrow range in ages of later basin-forming impacts, the late-stage heavy bombardment, and the lunar sample record of impact melt.

Laboratory Experiments: A series of laboratory experiments were performed using the NASA Ames Vertical Gun Range in order to assess the effect of impactor disruption on the cratering process. The experiments contrasted the effects of impactor velocity (v), angle (θ), and material properties (sound speed, c_p; density, δ_p) on crater depth and diameter in strength-controlled planer targets. Strength-controlled cratering preserves more clearly the evolution of coupling between impactor and target at early times. The same process occurs initially in gravity-controlled cratering but is eventually masked by the late-stage cratering flow field. As impact angle decreases (referenced to the horizontal), both peak pressure and the extent of the disruption in impactor and target decrease as $\sin^2\theta$. A hypervelocity vertical impact (90˚) at 15 km/s actually approaches a subsonic cratering event at low angles (e.g., a 15˚ impact results in peak pressures reduced to less than 7% of the vertical case) if energy coupling is controlled by first contact. Consequently, the strength/gravity-scaling transition may shift orders of magnitude to larger sizes if first-contact coupling controls the total energy partitioned to the target. First-contact coupling (peak pressure) is controlled by impactor velocity and density. If penetration depth (p) is scaled as (p/2r) $(\delta_t/\delta_p)^{1/3}$, then laboratory experiments show that this quantity simply depends on $(\delta_p v^2)^\alpha$ where $\alpha \sim 1/3$ for a given target. As impact angle decreases, however, the scaled penetration depth has a scaling exponent, $\alpha > 1/3$, i.e., lower angle impacts result in shallower than expected depths (Fig. 1). Comparably scaled transverse crater diameter, however, is found to depend only on $(\delta_t v_\theta^2)^{1/3}$ where $v_\theta = v\sin\theta$. In other words, maximum depth depends on the impactor density, whereas diameter depends on target density.

As the impactor continues to penetrate, it transfers its momentum and energy to the target as it disrupts and deforms. In planar targets, this transfer depends on the response of the impactor to the initial shock created at first contact, as well as $\delta_p v_\theta^2$. For ductile high-density impactors with $v_\theta > c_p$ (such as Cu), the transverse diameter exceeds expectations based on $\alpha = 1/3$ for impact angles less than 45˚. This transverse widening of apparent crater diameter relative to expectations reflects continued coupling between impactor and target during the penetration stage. The combination of reduced shock pressures uprange at first contact and delayed coupling along the trajectory downrange results in an oblong-shaped crater whose major axis is perpendicular to the trajectory for impact angles from 60˚ to 30˚ (6, 7). Experiments also reveal, however, that the crater shape in plan view changes as a function of the rate of energy transfer during oblique impacts. The rate of energy transfer depends on impact velocity and projectile/target impedance ($c_p\delta_p/c_t\delta_t$). Low velocity impact or soft coupling (low $c_p\delta_p/c_t\delta_t$) result in a pear-shaped crater with the apex pointing uprange. High velocity impacts or strong coupling (high $c_p\delta_p/c_t\delta_t$) result in a pear-shaped crater with the apex pointing downrange. In the former case, maximum coupling is delayed well after first contact; in the latter, it occurs at first contact with the downrange apex related to sibling impacts from the failed impactor. The reduced crater depth for oblique impacts relative to expectations for point-source scaling relations is attributed directly to decoupling a portion of the impactor as it ricochets downrange carrying away a significant fraction of the initial impactor energy and momentum (8).

As the radius of the impactor approaches the radius of the target (cylindrical or spherical), the effect of impactor decapitation on cratering becomes more evident (9). Experiments were performed with Lucite spheres and solid aluminum cylinders. Surface curvature allows impactor siblings (ricochet debris) to miss the target and to decouple completely from late-stage excavation downrange. In such cases maximum crater depth is only slightly reduced (Fig. 1); hence, first-contact coupling largely controls maximum penetration. Transverse apparent crater diameter on a curved surface is systematically smaller relative to a planar target for the same impact angle since the decoupled impactor no longer transfers its energy. The record of impactor debris, however, is documented on vertical witness plates downrange where the sibling impacts occur below the impact plane (surface tangent from first point of contact).

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At lower impact velocities, impactor failure occurs as simple shear. The angle of impact θ where one half of the impactor mass will be decoupled from the collison by shear can be simply defined as $\cos\theta = R/(r + R)$.

In summary, the vertical velocity component controlling the peak pressure at first contact only partly controls crater scaling relations for oblique impacts in strength-controlled cratering. For a given target, conditions at first contact (impactor density, velocity and angle) control the maximum depth. Crater diameter, however, is controlled by target density and energy losses from the decapitated impactor, particularly for curved surfaces. The combination of large relative size, low density, and low velocity can result in an initial penetration depth less than 10% of the impactor diameter at impact angles as large as 30˚.

Implications: The large "Backside Basin" seems to mandate special yet expected collision early in lunar history. This collision did not initiate significant mantle uplift in spite of its size and did not appear to result in extensive circumferential failure (multi-ring terraces). Even though massifs related to this impact are preserved, secondary ejecta scouring and multi-ring patterns are not. These enigmas can be understood from the energy-transfer processes associated with a large scale (r ~ 1000 km), oblique (<30˚), low density ($\delta_p \leq 2$ g/cm^3), and low velocity (5 km/s) body. The oblique trajectory and large scale resulted in a crater controlled largely by the lower half of the impactor: the upper half completely decoupled from later crater formation due to the effects of curvature. The low angle (30˚), low density, and low velocity resulted in a subsonic cratering event where the initial crater depth is only a fraction of the impactor diameter. Moreover, a low velocity would result in impactor failure well before penetration into the Moon and induce shear failure in both the target and asteroid. Laboratory experiments using a low-impedance veneer significantly reduces impactor penetration into a stronger substrate. The lunar (and asteroid) megaregolith serves a similar purpose to decouple most of the impactor more effectively after first contact but before significant penetration. In contrast with the familiar effects of hypervelocity oblique impacts producing oblong craters with a butterfly ejecta pattern, the proposed collision will produce compressional deformation and ejecta distributed in a fan-shaped pattern open downrange.

There are several important implications of this proposal. First, the impactor may have been a companion Moon in earth orbit (~4.0 by) in order to meet the conditions of a low encounter velocity. Second, the preserved massifs and thickening of the anorthositic crust on the farside (4) are consistent with a trajectory from the south. Third, the stream of surviving impactor debris should have contributed to a cataclysm of basin-forming impacts over the next 0.2 by and perhaps the so-called catastrophic bombardment enigmatically late in lunar history. Such a suggestion is consistent with the general absence of melts in lunar samples older than 4.0 by (10) but now invokes a major not-so-near miss to generate the circum-terrestrial debris swarm. Fourth, the low impact angle, low velocity, and coupling process with the upper lunar crust should have generated extensive friction melts retained in the basin (10).

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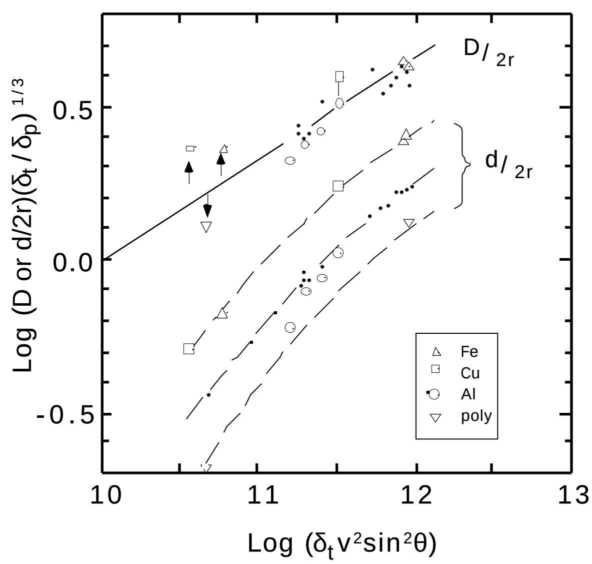

Fig. 1 Effect of the vertical component of impactor velocity (angle) and density on the transverse crater diameter and depth normalized by impactor diameter (2r) and density ratio for craters produced in solid aluminum. Impactor density does not significantly affect the transverse crater diameter, i.e., perpendicular to the trajectory, but does result in an offset for crater depths. At low impact angles (<45˚), crater depth becomes shallower than expected due to energy losses from the ricochet fraction. This appears to be enhanced on a curved surface (circles).