N92-10856

ATMOSPHERIC EFFECTS ON OBLIQUE IMPACTS;

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Laboratory experiments and theoretical calculations often use vertical impact angles (90°) in order to avoid the complicating effects of asymmetry. Nevertheless, oblique impacts represent the most likely starting condition for planetary cratering (1, 2, 3). Gault and Wedekind (2) provided a classic study of the effect of impact angle on crater morphology and crater scaling. More recent studies (4, 5) have underscored the importance of impact angle on energy partitioning and the implications for projectile survival. When an atmosphere is introduced, the change in energy partitioning is dramatically revealed as kinetic energy carried away by the projectile is rapidly converted to thermal energy (3,4). Additionally, the presence of an atmosphere affects the cratering process at laboratory scales by adding atmospheric pressure to lithostatic pressure, by introducing viscous drag, and by introducing strong dynamic pressures associated with the projectile wake (6). For gravity-controlled growth, such effects are expressed by reduced cratering efficiencies, reduced crater aspect ratio (due to arrested crater growth), and increased turbulent power affecting the styles of ejecta emplacement (7). Changing both impact angle and atmospheric pressure not only allows testing previous results for vertical impacts but also reveals phenomena whose signatures would otherwise be masked in the planetary cratering record.

LABORATORY EXPERIMENTS: The laboratory studies were performed with the NASA-Ames Vertical Gun Range (AVGR), which is a national facility for investigating impact cratering processes. Impact angles at the AVGR can be increased from 0° to 90° in 15° increments while maintaining a flat target surface (see 2). The launch tube is isolated from the target chamber through the use of a thin mylar diaphragm which does not modify sufficiently large (≥ 0.1 cm) and strong (aluminum) projectiles. The large target chamber allows tracing the effects of both entry and ricochet without complex interactions created by the chamber walls. Different atmospheres (nitrogen, argon, and helium) characterized the effects of both gas density and mach number. Targets varied according to purpose: dry-ice (powder and blocks), carbonates, plasticene, and aluminum blocks were used to study early-time phenomena; compacted pumice, loose sand, low-density microspheres, and powdered dolomite emphasized aerodynamic effects on crater scaling and ejecta emplacement. Because of the complexities in atmosphere-impactor-ejecta interactions, no single combination allows direct simulation of a planetary-scale (10-100 km) event. Nevertheless, fundamental processes and observed phenomena allow formulating first-order models at such broad scales.

PHENOMENOLOGY: Five important early-time processes emerge as impact angles decrease and have implications for recognizing planetary signatures. First, the energy partitioned to the projectile at impact does not appear to be significantly changed: downrange ricochet fragments initially retain 50-80% of the original impactor kinetic energy. Nevertheless, these fragments directly and quickly couple with the atmosphere and result in rapid deceleration and intense heating downrange. Scouring of the downrange target surface and the paucity of smaller pits produced on downrange witness plates indicate that drag and turbulence effectively entrained the ricochet debris. Second, ionized vapor generated at impact (separate from the jetting process) is progressively changed with increasing atmospheric pressure (P) from an expanding hemispherical cloud moving downrange (low P) to a tight fireball pursuing ricocheted fragments (high P) at low angles (15°). Third, interactions between the impact-generated vapor cloud and the early-time impact cavity change significantly with impact angle. At high impact angles (≥ 45°) the ionized cloud is contained and redirected uprange as a jet (3, 8). Consequently energy coupled with the surrounding atmosphere (and related blast effects) is significantly reduced soon after first contact between impactor and target. Fourth, early-time high-speed ejecta quickly establish the classic cone shape but this profile becomes increasingly asymmetric (high uprange, low downrange curtain angle) as impact angle decreases. This ejecta plume further confines the vapor cloud for higher angle impacts, thereby further decoupling the cloud from the atmosphere. Fifth, the heated atmosphere behind the projectile rapidly closes (within a projectile radius). Consequently, the projectile wake not only forms an ionized tube, but gases within this wake pursue the projectile at a comparable velocity. For higher angle impacts, the pursuing wake gases are partly confined within the ejecta plume and are effectively decoupled from the surrounding atmosphere. For lower angle impacts, wake gases separated from the projectile pursue the ricochet debris. These five processes generally occur within the first 10% of the time required to form the crater in particulate targets. Their effects, however, are clearly expressed on the target surface beyond the continuous ejecta facies as atmospheric pressures increase.

Evolution of both the ejecta curtain and late-stage crater excavation cavity is modified by dynamic pressures within the atmosphere. At high impact angles, the ejecta curtain angle increases as aerodynamic drag effects increase (increased atmospheric density, decreased particle size or density). For oblique impacts, a similar change in ejecta curtain angle is observed. One consequence is considerable asymmetry in the ejecta patterns at unexpectedly high impact angles (60°). Although early-time asymmetries in the ejecta curtain are lost at late times under vacuum conditions, considerable azimuthal asymmetry remains in ejecta thickness. Under atmospheric conditions, this asymmetry is enhanced. Impact angles as high as 60° resulted in butterfly ejecta lobes for craters in compacted pumice and atmospheric pressures of nearly one bar. Under vacuum conditions, the butterfly pattern does not become evident until much lower angles (<10°). At high atmospheric pressures, ejecta emplacement is further modified by airflow drawn by the downrange-moving assemblage of ricocheted fragments, vapor, and wake gases.

Previous studies (2) documented that cratering efficiency (displaced target mass/projectile mass) decreases as sin θ for particulate targets (including pumice) and $\sin^2\theta$ for strength-dominated targets. This decrease can be understood if the vertical component of impact velocity principally controls scaling. For gravity-controlled cratering, this result can be simply expressed in terms of the dimensionless π_2 parameter as $gr/(v\sin\theta)^2$ as suggested in (9). Under vacuum conditions, cratering efficiency for pumice decreases as $\pi_2^{-\alpha}$ with $\alpha = 0.52$ (10); hence, cratering efficiency changes as $(v\sin\theta)^{1.04}$. Under atmospheric conditions cratering efficiency was significantly reduced; nevertheless, the power-law dependence on impact angle remained essentially constant with a value of 1.1 from 30° to 90°. This result indicates atmospheric pressure and drag modifies gravity-controlled crater growth even at oblique angles.

PLANETARY IMPLICATIONS: Under the dense atmospheres of Earth and Venus, impact-generated vapor and entrained projectile material from oblique impacts (<30°) should largely decouple from crater excavation, thereby affecting the surface downrange prior to ejecta emplacement. The character of this cloud in the laboratory evolved into a lobe of turbulent, ionized gas and the atmosphere constricted lateral expansion as aerodynamic drag reduced its downrange velocity. The lateral extent of this cloud scaled to the original impactor diameter will depend on $(\delta k v^2/\rho)^{1/3}$ where δ and v are the density and velocity of the projectile, respectively; with ρ representing the ambient atmospheric density and k an efficiency factor for the fraction of the impactor energy coupled to the atmosphere. The efficiency factor depends to a large degree on impact angle (given impact velocity) not only due to the role of projectile ricochet and target heating but also due to interference created by the early-time transient cavity. For a value of k = 0.1 and lateral growth reduced to 700 m/s, the lateral expansion on Mars would exceed 100 projectile diameters, whereas on Earth and Venus this value would reduce to about 30 and 10, respectively. Numerical models reveal that a 1 km complex of vapor/melt/debris exiting at 15° with an initial velocity one half the impactor velocity would escape the atmospheres of Mars and Earth but would be rapidly decelerated (within 300 km) on Venus. Hence, signatures of early-time phenomena associated with jetting and vaporization should be a widespread scour zone on Mars (11), a turbulent downrange fireline on Earth (4), and a turbidity flow emerging from below the later stage ejecta facies on Venus.

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