ATMOSPHERIC EFFECTS AND OBLIQUE IMPACTS: COMPARING LABORATORY EXPERIMENTS WITH PLANETARY OBSERVATIONS. Peter H. Schultz, Brown University, Department of Geological Sciences, P. O. Box 1846, Providence, RI 02912, peter_schultz@brown.edu

Introduction: Without direct observations of a major impact, one of the few ways to study the impact process is by assessing the effects of its environment (gravity, atmosphere) or conditions of impact (e.g., impact angle). The purpose of this contribution is to review selected consequences of both the atmosphere and impact angle as witnessed in laboratory experiments or revealed by large-scale craters preserved on different planets.

Atmospheric Effects: The lunar impact cratering record is an invaluable template for interpreting the pristine cratering record on other planets. In addition to its lower gravity, the absence of an atmosphere simplifies the cratering process. While it is often assumed that the tenuous atmosphere of Mars is overwhelmed by both the initial blast and the later advancing ejecta curtain, this assumption can be shown to be unwarranted. The atmosphere does play a significant role in modifying the late-stage ejecta emplacement but this role changes as a function of target, scale, and atmospheric pressure/density. The challenge is to identify meaningful tests to isolate this effect from other processes whether through statistical studies of the planetary cratering record or by case studies.

Laboratory impact experiments provide fundamental clues for assessing atmospheric effects since the process is complex and evolving. Such experiments are not just one-to-one comparisons between results in the laboratory and examples on the planets. Rather they should be designed to isolate variables in order to enable appropriate extrapolations. For example, performing an impact experiment at 100 bars to reproduce conditions on Venus or 6mbars to simulate conditions on Mars would only produce a crater of that particular size, in that specific target. Such laboratory observations combined with theory have yielded important predictions that can be tested by the planetary impact record. Applications to Mars and Venus illustrate this strategy which elevate the discussion beyond "look-alike" comparisons.

The distinctive ejecta facies surrounding craters on Mars have generated a range of interpretations. The fluidized appearance has commonly been used to interpret the presence of buried water (1, 2). Although popular ("follow the water" theme), this could be the planetary equivalent of a mirage. It is valid to assume explicitly that fluidized ejecta represents the presence of water and then explore the implications of this extrapolation; it is not valid, however, to simply state that fluidized ejecta deposits provide evidence for water. The problem is more ambiguous….and much more interesting.

Extensive laboratory impact experiments demonstrated that the response of the atmosphere to the crater formation is as important as the effect of the atmosphere on the ejecta. Early studies noted that the atmospheric drag acting on individual ejecta should be profound, even on Mars (3). For a given crater size (hence ejection velocity at the same stage of crater growth), atmospheric drag arrests the ballistic range over a relatively narrow size range of the ejecta (factor of 10) when scaled to the ambient atmospheric density. Conversely, for a given atmospheric density and ejecta size, the effect of drag increases with increasing crater size. If blindly applied, such considerations predict that ejecta would never get out of the crater for very fine-grained ejecta (25 microns in laboratory experiments and centimeter sizes for 10 km-diameter crater on Mars). But both experiments and the existence of excavated craters on Mars (not to mention Venus) demonstrate that craters do form. The paradox was resolved by recognizing that kinematic flow created by the outward moving ejecta curtain set up intense vortices that entrain sufficiently small decelerated ejecta (4, 5). Moreover, the presence of even a small fraction (10% by weight) of such a fine-grained component can change ballistically ejected material into a vortex with tornadic velocities. Then by isolating the controlling variables, later studies were able to compare models of the kinematic flow field with simplified experiments using controlled conditions in a wind tunnel (6, 7).

Such comparisons between models and observations both in the laboratory and on planetary surfaces led to specific predictions for ejecta deposits on Mars (4, 5, 8). First, onset for fluidized ejecta should depend on crater size due to the combination of increased ejection velocities and decreased ejecta sizes (comminution). Second, run-out distances scaled to crater radius should be proportional to crater size on Mars due to increasing ejecta entrainment (but decrease on Venus). Third, increased run-out distances with increasing latitude reflect an increased fraction of fine-grained sediments. Fourth, rampart-terminated ejecta facies represent coarser grained fractions that were mobilized but not fully entrained; hence, "rampart craters" should characterize the mare-like ridged plains rather than water-filled substrates. Fifth, radial facies indicate enhanced explosive expansion and hence the most (rather than the least) volatile-rich targets (or have been extensively modified). Sixth, anomalously long ejecta run-out distances can be created by autosuspension that feeds the vortex or flow with energy or gas (e.g., near-surface volatiles entrained by basal ejecta flow). Ninth, the development of late-stage ejecta-entrained vortices will not be significantly affected by the surrounding disturbed atmosphere (heated) since such blast effects rapidly equilibrate in the tenuous Martian atmosphere and do not drastically affect the results (8).

The above list of predictions and observations challenge some models of ejecta emplacement imposing only water. Nevertheless, the presence of volatiles can be recognized, whether in post-emplacement flow of water-lubricated near-rim ejecta or in enhanced run-out through autosuspension. Ironically, the critical importance of fine-grained lithologies may reflect enhanced weathering conditions (including fluvially transported sediments) during the Noachian and Hesperian and the role of climate-controlled processes (e.g., polar sinks for dust, obliquity changes, and polar wandering). Such considerations will not resolve the debate about Martian cratering. It simply challenges interpretations and assumptions to look further than the translating the term "fluidized" into "water-entrained".

Oblique Impacts: Until relatively recently, full three-dimensional models of hypervelocity impacts have not been possible. As a result, important clues about the impact process have been gleaned from laboratory experiments compared with the planetary cratering record. Advances in computing power now has not only allowed more widespread use of 3-D codes (e.g., 9) but also enabled new diagnostics in the laboratory. These parallel advances will permit unprecedented opportunities to validate the codes and to test extrapolations to large scales, whether directly from laboratory experiments or comparisons with the codes. The oblique impact process represents one of the most challenging of these tests.

Oblique impacts map time into space. During vertical impacts, rapid changes in the transfer of energy and momentum from impactor to target are generally lost or overprinted by each successive stage of formation. Oblique impacts, however, expose this transfer along the initial trajectory. Laboratory experiments have long documented the overall change in crater dimensions and ejecta distributions (10), but new studies are providing other possible strategies for identifying the initial trajectory. First, direct measurements of far-field pressures reveal that oblique impacts cannot be simply modeled using point-source assumption (11). These measurements are clearly captured in asymmetries, timing, and nature of failure in three dimensions. Such laboratory measurements are also captured in recent computational models (9). Second, three dimensional particle image velocimetry (3D-PIV) is capturing the evolving flow field expressed by ejecta leaving the crater (12, 13). The enigmatic oblong crater shape perpendicular to the trajectory for modestly oblique impacts is now recognized in the ejecta flow field in addition to failure patterns in strength-controlled craters. Third, high-speed imaging and novel experimental designs are capturing the contact and failure pattern of the projectile.

Applying such laboratory experiments to planetary-scale phenomena and processes cannot be made without analytical or computational modeling. For example, the crater/projectile dimension ratio for cratering in sand for hypervelocity experiments is 50:1. But this ratio for large-scale (100 km) craters approach 15:1. Because oblique impacts reduce the peak pressure in the target, this ratio decreases still further to 8:1. Consequently, large-scale cratering more closely resembles strength-controlled laboratory impacts in terms of the relative dimensions of the crater and impactor. This also means that the transition from the region controlled by the transfer of momentum and energy becomes a significant fraction of the crater at large scales. Hence, observational evidence of the trajectory becomes more evident as well.

Observational evidence for impact trajectory (e.g., 15, 16) includes asymmetries in shock effects expressed by erasure/survival of pre-impact structural control, crater shape in plain view (whether oblong perpendicular to or along the trajectory), uprange offset of the central peak, breached central ring downrange, and downrange ricochet effects. Not all craters will exhibit such features. In addition to changes in expression with scale, impactor density and velocity also will play a role. For example, very high-velocity oblique impacts (>40km/s) will increase the crater/projectile ratio and partition more energy to melting and vaporization. Target topography (relative to the scale of the impactor) also can be shown to radically modify early-stage coupling processes. Consequently, statistical studies of crater morphologies may not reveal the key signatures. Such an approach is similar to including a failed experiment in laboratory impacts.

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