IMPACTOR FOOTPRINTS OR TRANSIENT CRATERS: ORIGIN OF BASIN GRAVITY ANOMALIES. P. H. Schultz, Department of Earth, Environmental and Planetary Sciences, Brown University, 324 Brook St, Box 1846, Providence, RI, 02912; peter_schultz@brown.edu.

Background: Identification of the transient craters in large two-ring and multi-ring basins remains problematic. One model maintains that there is no expression of the initial transient cavity due to wholesale collape [1, 2]. A second model proposes that one of the interior rings represent a relict structure of the transient cavity [3]. A third model suggests that the interior ring and gravity high do not reflect the limit of the transient crater but rather the downward displacement related to the initial compression stage of cratering (subsequently uplifted) [4, 5, 6] or perhaps a zone of impact melting [7]. Analysis of recent detailed gravity data links the annular crustal bulge to the original gravity-controlled transient cavity, which was erased during collapse [8], whereas results from GRAIL mission now clearly tie the central Bouguer anomaly to the inner ring without indicating a connection to the transient crater [9]. Regardless of the details in the various models, new GRAIL data demonstrate that gravity highs in peak-ring basins link with the innermost rings of both peak-ring and multi-ring basins, thereby implicating a connection between the innermost ring and the innermost ring of multi-ring basins [9]. Nevertheless, questions remain about the significance of this connection. In the discussion that follows, the following abbreviations are used: CPkC for central peak craters; PR, peak ring; PRB, peak ring; MRB, multi-ring CD; and crater diameter.

Considering Alternatives: Each model makes different predictions. If the peak rings of PRB, innermost ring of MRB (and inner Bouguer anomaly) reflect the transient cavity, then relics of pre-collapse features should not survive beyond the inner ring (at least in models of oscillating gravity collapse). Moreover, all expressions of oblique trajectories should be erased including uprange offsets, breached interior rings, and pre-collapse ejecta scours.

If the peak ring of PRB and innermost ring of MRB reflect the transient cavity but *do not* undergo oscillatory gravity collapse, then the following observations could be made: (a) expressions of impactor trajectory could be preserved within the basins on the mega-terrace; (b) fragmental expressions of impactor trajectory might be preserved within the basins beyond the inner ring; (c) decreasing impact angles should result in larger PR diameter to CD ratios; (d) higher impact speeds should result in the same PR diameter to CD ratio on a given planet; and (e) gravity should be the controlling variable for the CPkC to PRB size transition on different planets, i.e., no velocity component.

If the interior ring reflects initial conditions of the impact, then different scaling relations control its dimension relative to the final transient cavity in PR basins. Here this is called (for convenience) the *Footprint* (*FP*) model. First, the transition from CPkC to PRB should include a velocity component as well as gravity. Second, PR basins and CPk craters could occur on the same body as the result of different impact velocities. Third, highly oblique impacts should result in shallow excavation with reduced collapse yet clear expression of downward displacement related to the displacement footprint and lateral flow. Fourth, decreasing impact angles should result in different central Bouguer anomalies for the same-size crater/basin diameter. And fifth, there should be a wide range of expressions of impact trajectory including (excluding ejecta asymmetries): (a) The PR diameter to CD ratio should increase with decreasing impact angle; (b) The PR diameter to crater-diameter ratio for a given size crater/basin should depend on the average impact speed at each body; (c) Asymmetric collapse results from deep displacement uprange and shallow excavation downrange; (d) Expressions of asymmetries in peak pressures should remain.

Impactor Footprints: Laboratory experiments provide a possible physical basis for the downward-displaced footprint. Impacts into curved surfaces (aluminum cylinders) reveal crater sizes that dramatically decrease with decreasing impact angles as a significant fraction of the initial kinetic energy is carried away by the escaping sibling fragments, a result also captured in computer models [10]. Nevertheless, laboratory experiments reveal a deformation pit indicating that maintains the same size (and same speed), even as crater diameter decreases. The limiting dimension of this pit may reflect a strength limit following the decay in the downward directed shock [5]. Hydrocode models also capture this process that marks the transition from downward displacement to lateral flow [4]. If strength is not included, hydrocode models erase this record, especially for vertical impacts. With decreasing impact angles, however, peak pressures decrease and the cratering flow field migrates downrange, thereby preserving the signature of the impactor footprint. The footprint diameter scaled to the impactor diameter depends on $(\delta_t/Y_o)^{\mu/2} (v)^{\mu}$ and is independent of gravity-controlled growth [11].

Discussion: Such observations provide possible answers the various questions to the various questions raised by the different models. First, earlier observations of CPkR and MRB on Mercury, Moon, and Mars proposed that there was a velocity, as well as a gravity signature in the transition diameter [12, 13], an observation subsequently confirmed from new data from the Messenger data [14]. Second, both peak-ring basins and central peak craters do occur at the same diameter on both Mercury and Mars, explainable by differences in impact velocities [11]. While the impact-melt model also would accommodate such differences, the predictions are very different. The FP model predicts that the PR:CD ratio should increase with decreasing impact angle, whereas the melt model predicts that this ratio should decrease due to reduced melting at lower impact angles. The different scaling relations for diameter and impactor footprint illustrate the contrasting effects on the zones of melt, displacement, and crater size (Fig. 1).

Oblique impacts allow testing the FP-model further. At impact angles below about 20°, the portions of the impactor decouples (decapitates) from the main mass and impacts progressively farther downrange with decreasing impact angle. Impact survivors are termed "siblings" in order to differentiate this component from primary ejecta derived from the target. This process is clearly evident in laboratory experiments and planets [5] and hydrocode models [6]. This is best expressed at lower impact speeds, e.g., the Moon and Mars where surviving fragments impact downrange. At very low angles (<10°), however, impactor fragments fully escape the transient cavity, e.g., parallel ejecta downrange from the grazing Messier Crater. Between 20° and 30°, however, this process produces significant pre-excavation scouring, which remains on the rim and walls of the peak-ring Schrödinger Basin and across the floor of Antoniadi [15]. At still larger scales, sibling debris may produce a downrange companion crater, which may be partly consumed during the excavation stage but preserved at depth in the modification zone (between the inner ring and outer scarp). This process was proposed to account for the shape of the inner-ring of Moscoviense [6]. The Bouguer anomaly in Moscoviense revealed by GRAIL [9] is consistent with such a deep relict sibling impact that was not erased due to shallower excavation downrange [e.g., 10]. The same process accounts for positive anomalies on the downrange within Orientale and Crisium.

Conclusions: Bouguer anomalies in peak-ring and multi-ring basins are most consistent with expressions of the penetration/compression stage of cratering rather than the transient cavity. This perspective allows calibrating scaling relations, constraining excavation depths, and understanding the relative dimensions of central peak rings and inner rings of basins.

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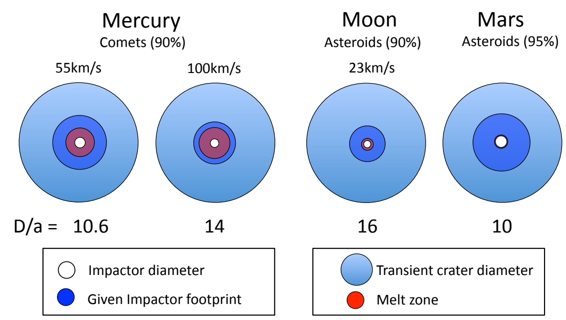

Fig. 1a: Comparing the effect of impact speed and gravity on both the melt zone (red) and impactor footprint (dark blue) for the inner planets based on scaling relations incorporating gravity, velocity, impactor diameter (a), and expected density impactor/target impedance contrasts. If related to the impactor footprint, the ratio of the inner-ring diameter of basins to the transient diameter (D) on Mars should be larger or comparable to Mercury but larger than on the Moon.

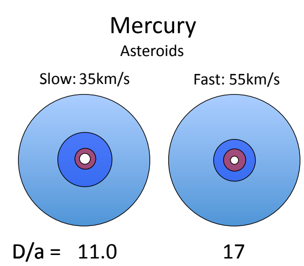

Fig. 1b: Effect of lower speed asteroid impacts on the interior ring diameter on Mercury. Lower speeds result in larger inner rings but reduced melt zones for the same size crater on Mercury.