Decoding inner solar system bombardment from crater populations

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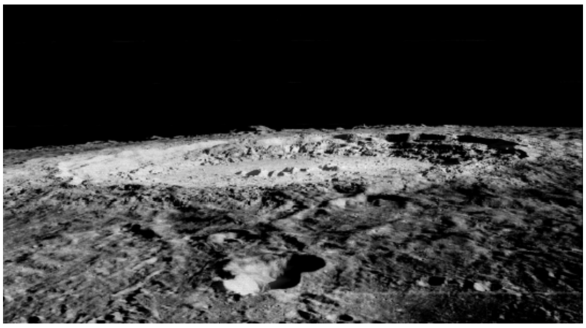

Encoded in the population of impact craters on a planetary surface is a record of the severity, source and timing of its bombardment. The oldest surfaces of the Moon and Mars provide evidence of the most formative and yet violent period of solar system history: the first billion years. To infer information about the population of impacting objects, the surface age and subsurface properties from a planet's crater population requires a fundamental understanding of how the size and shape of each impact crater relates to the properties of the impactor and target. This is known as crater scaling. While recent progress has improved our understanding of crater scaling for small, simple craters and the largest mega-basins, impactor-to-crater scaling of mid-sized, so-called "complex" craters, 10-300 km in diameter, remains elusive and controversial. The aim of this project is to exploit new model developments and observations from lunar, martian and cerean craters to improve crater scaling relationships for this important size-range of craters. These advances will improve our understanding of the severity, timing and source of early inner solar system bombardment; the ages of all planetary surfaces, including the possible resurfacing age of Venus; the mass flux of volatiles and organics added to Earth after accretion; the current asteroid hazard; and the thermal, chemical, and physical evolution of planetary crusts and asteroids.

Crater scaling crisis? The widely-used conventional approach to crater scaling [e.g., 1] has recently been challenged. Bottke et al. [2] showed that conventional complex crater scaling relationships, when applied to the well-characterized size-frequency distribution (SFD) of 1-10 km Near Earth Objects (NEOs), are incompatible with the observed SFDs of 10-200 km diameter craters on Venus, the highlands of Mars and the lunar farside in the last 3 Gyrs (Fig. 1). Instead, the crater SFD in each case is remarkably consistent with the observed NEO SFD when a simple linear scaling is applied, in which crater size is a factor $f \approx 24$ times impactor size (Fig. 1; referred to here as $f24$ scaling). The difference between these two scaling approaches is profound; for a 200-km crater the difference is a factor >2 in impactor diameter and 10 in mass.

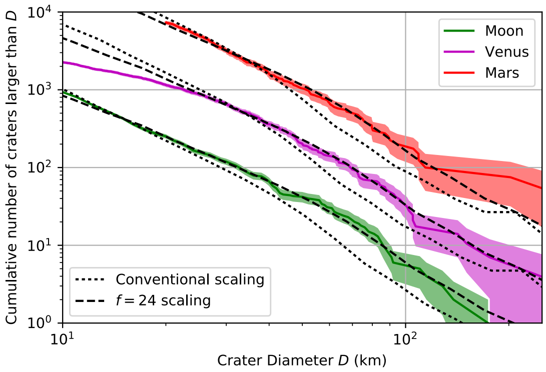

Figure 1 Crater populations on the Moon, Mars and Venus [after 2] (shading denotes uncertainty) compared with predictions based on the NEO population and crater scaling laws. To show on one plot, N(>D) has been scaled for Venus and Mars.

The importance of re-evaluating crater scaling: This controversy prompts an urgent re-evaluation of crater scaling relationships, with major implications depending on the outcome. Is something missing from the conventional crater scaling approach that can reconcile the NEO and crater populations? Or are the scaling laws correct, implying that the current observed NEO population is not representative of the historical impact flux in the inner solar system? The latter would constitute a major paradigm shift, while revised scaling equations could have major implications for crater model ages of planetary surfaces, regolith production, the consequences of the Late Heavy Bombardment, and the current impact hazard. For example, existing estimates of Venus's surface age based on its population of ~900 craters and using conventional crater scaling are 500-750 Ma. Using $f24$ scaling revises the surface age estimate down to 130-250 Ma [2]. Moreover, models of the flux of 10-100-km diameter asteroids during the Late Heavy Bombardment agree well with the population of >300 km lunar craters and terrestrial Archean spherule layers when $f24$ scaling is used [3]. Using conventional scaling, however, the same fluxes are more than an order of magnitude too low to explain observations and require an impactor population with a SFD with fewer large objects compared to the main asteroid belt [1].

The project: The aim of this project is to use numerical modelling, combined with new observational constraints on crater formation, to resolve recent controversy in crater scaling. Computer modelling is required owing to the profound role of gravity-driven collapse that is not reproducible in laboratory-scale experiments. Recent simulations of cratering on Earth [4] provide a template for testing conventional scaling equations [1], but several factors now prompt a comprehensive numerical study, including: new insight into crustal properties of the Moon [5] and the importance of porosity [6] and temperature [7] for crater formation; recent advances in impact modelling for simulating impacts on porous crusts [4] and complex crater formation in three dimensions; and new observational constraints on crustal structure beneath large lunar craters from NASA's GRAIL mission [8].

The proposed work will entail a comprehensive numerical modelling study of complex crater scaling in four environments: the Moon, Mars, Venus and small bodies with varying ice content. The project will use the iSALE shock physics code to quantify the effects of various impactor and target properties on impactor-to-crater diameter scaling, using the full 3D version of iSALE as appropriate. This is all within existing functionality and achievable: typical iSALE2D simulations run to completion in a few days on a single core; iSALE3D simulations can be completed in a few days to weeks on many cores. From the comprehensive database of numerical simulations produced, we will develop improved crater scaling equations and resolve the crater-scaling crisis [2] and we will investigate three outstanding questions in impact crater scaling:

1. Complex crater scaling on the Moon (and Mars): the role of porosity - NASA's GRAIL mission revealed that the Moon's crust has a low bulk density and contains significant (5-20%) porosity to a depth of at least several km and perhaps the base of the crust. However, preimpact porosity is not considered in conventional complex crater scaling: its influence has only recently been investigated numerically [6], thanks to our recent improvements to iSALE's material modelling capabilities [4], and could increase cratering efficiency if dynamic weakening during impacts is more efficient in higher porosity materials. The effect of large-scale crustal porosity may also be important on Mars and other airless bodies. Simulation results will be validated using high-resolution morphometric measurements of lunar complex craters and gravity-derived crustal thickness profiles beneath large lunar craters [8]. Results will help constrain the severity and timing of the Late Heavy Bombardment [1,3].

2. Complex crater scaling on Venus: the role of temperature - Current crater model ages of Venus' surface invoke conventional crater scaling, appropriate for cold rocky targets. However, our recent simulations of large (>300 km) impact basins on the early Moon have revealed the important role of preimpact target temperature on basin size [e.g., 7]. A difference of +500 K at the base of the Moon's crust can imply a factor of two increase in basin size [7]. As current near-surface temperatures on Venus are comparable to those at the base of the lunar crust during the basin-forming epoch, crater formation on Venus may be substantially more efficient than previously assumed and hence Venus' surface age might be significantly overestimated. Our simulations will test this hypothesis.

3. Cratering on asteroids (and Mars): the role of ice content - Recent observations of asteroids have found abundant water-ice [e.g., 9]; instead of a clear distinction between dry asteroids and ice-rich comets, small bodies exist on an asteroid-comet continuum [10]. Crater scaling in ice and rock is very different; up to a factor of two in impactor diameter (10 in mass) for a 10-km crater on an asteroid the size of Ceres. This corresponds to a ~50% uncertainty in crater model age for a typical asteroid surface. To reduce this uncertainty, we will establish the extent to which the rock or ice component controls the strength (and thus crater size) and surface viscosity (and thus relaxation timescale) of ice-rich bodies. Simulation results will be tested against the crater size-morphology progression observed on Vesta and Ceres by the Dawn spacecraft [11].

References: [1] Johnson BC *et al.* (2016) *Icarus* 271: 350–359. [2] Bottke WF *et al.* (2016) *LPSC XLVII Abs.* #2036. [3] Bottke WF *et al.* (2012) *Nature* 485: 78–81. [4] Collins GS (2014) *JGR-Planets* 119: 2600-2619. [5] Wieczorek MA *et al.* (2012) *Science* 339: 671-675 [6] Milbury C *et al.* (2015) *GRL* 42: 9711–9716. [7] Miljković K *et al.* (2013) *Science* 342: 724–726.[8] Neumann GA *et al.* (2015) *Sci. Adv.* 1: e1500852. [9] Rivkin AS & Emery JP (2010). *Nature* 464: 1322–1323. [10] Hsieh HH (2017) *Phil. Trans. R. Soc. A* 375: 20160259. [11] Hiesinger *et al.* (2016) *Science* 353: 1003-1004.