**ON ASTEROID IMPACTS, CRATER SCALING LAWS, AND A PROPOSED YOUNGER SURFACE AGE FOR VENUS.** W.F. Bottke[1], D. Vokrouhlicky[1,2], B. Ghent[3], S. Mazrouei[3], S. Robbins[1], S. Marchi[1]. [1]Southwest Research Institute and NASA's SSERVI-ISET Team, Boulder, CO, USA (bottke@boulder.swri.edu) [2]Institute of Astronomy, Charles University, Prague, Czech Republic. [3]Department of Earth Sciences, U. Toronto, Canada.

**Motivating Problem**. A fascinating on-going debate concerns the asteroid sizes needed to form large craters. For example, numerical hydrocode models predict that $D_{ast}$ > 15-20 km and $D_{ast}$ > 8 km diameter asteroids are needed to produce large craters like Chicxulub ($D_{crat}$ ~180 km) and Popigai ($D_{crat}$ ~100 km), respectively [e.g., 1]. Curiously, the abundance of extraterrestrial Ir/Os measured at well-characterized impact boundaries on land and in oceanic cores predicts far smaller asteroids [e.g., 2-4]. Using Ir/Os data from [4], combined with realistic asteroid bulk densities, we compute projectile sizes for these craters that are $D_{ast}$ > 7-8 km and $D_{ast}$ > 3-4.5 km, respectively. *The difference can be substantial; a factor of ~10 in mass!*

To investigate this by proxy, we decided to empirically determine the crater scaling law that allowed the present-day near-Earth objects (NEOs) to reproduce the younger crater populations on the Moon, Venus, and Mars. We restricted our analysis to $D_{crat}$ >10-20 km that are ≲ 3 Ga. We believe our method has promise because the NEO size frequency distribution (SFD) is > 90% complete for $D_{ast}$ > 1 km [5] and the *shape* of the NEO SFD (and its source, the main belt SFD) has likely been in quasi-steady state for ~3 Ga [6].

**Lunar Craters**. For the Moon, we mapped the NEO SFD into Copernican/Eratosthenian-era craters ($D_{crat}$ > 10 km; ≲ 3 Ga) [7]. Our crater scaling law function, *f*, was a simple ratio between crater and projectile diameters (i.e., $f = D_{crat} / D_{ast}$). As a comparison, we also plot what happens when the NEO SFD is modified by scaling laws designed to reproduce hydrocode results [e.g., see [1] for approximations].

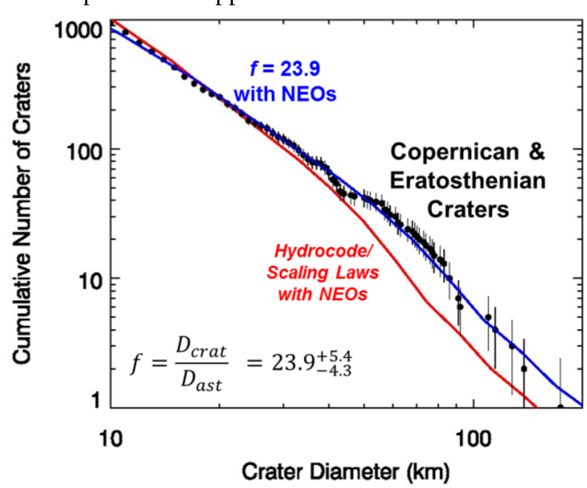


**Fig. 1.** Comparison between lunar craters <3 Ga (black) and modified NEO SFD. Asteroid diameters were (blue) multiplied by *f* = 23.9 and (red) input into a crater scaling law designed to match hydrocode results.

**Fig. 1** shows our best fit results for *f* = 23.9 (1σ errors of +5.4, -4.3). The main features of lunar crater SFD are reproduced by linear scaling at all sizes. In contrast, hydrocode scaling shows an increasing mismatch for $D_{crat}$ > 40 km, and their best fit can be ruled out at the 2σ level. The reason is that hydrocode scaling requires proportionally larger projectiles to make big craters, and there are not enough sizable NEOs to make up the difference.

**Venus Craters**. Venus has ~900 craters distributed randomly across its surface [8]. Here we mapped the NEO SFD into $D_{crat}$ > 25 km craters, the size where "crater fields" produced by atmospheric disruption events start to become plentiful. Our best fit, *f* = 24.4 (+6.3, -4.7), is shown in **Fig. 2**. As before, we find that linear scaling matches all the main features of Venus' crater SFD, and that hydrocode scaling yields a substantial mismatch for $D_{crat}$ > 40 km craters.

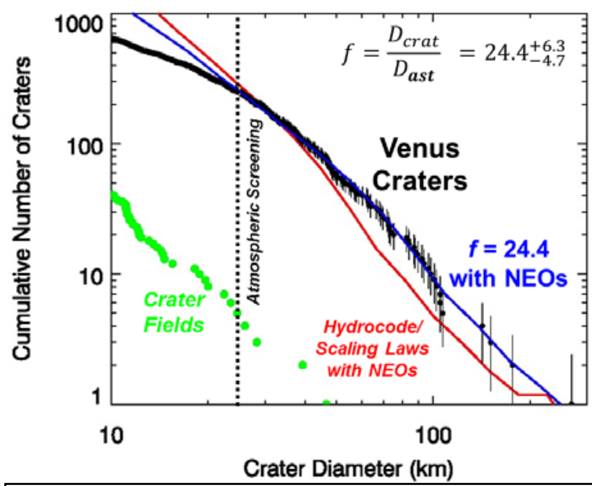


**Fig. 2.** Comparison between Venus craters (black) and modified NEO SFD. Asteroid diameters were (blue) multiplied by *f* = 24.4 and (red) input into a crater scaling law designed to match hydrocode results.

**Mars Craters**. For Mars, we examined craters found on Late Hesperian lowland terrains (≲ 2.8-3.4 Ga) [9]. Note that some terrains here are old enough to have obtained a few large $D_{crat}$ > 200 km craters from the late heavy bombardment [10]. We focus here, however, on fitting 20 < $D_{crat}$ < 200 km craters where the majority of the crater data is located.

Our best fit case here is slightly lower than before, with *f* = 19.8 (+8.0, -4.4) (**Fig. 3**). Interestingly, the decrease is driven by a slight "notch" in the crater SFD

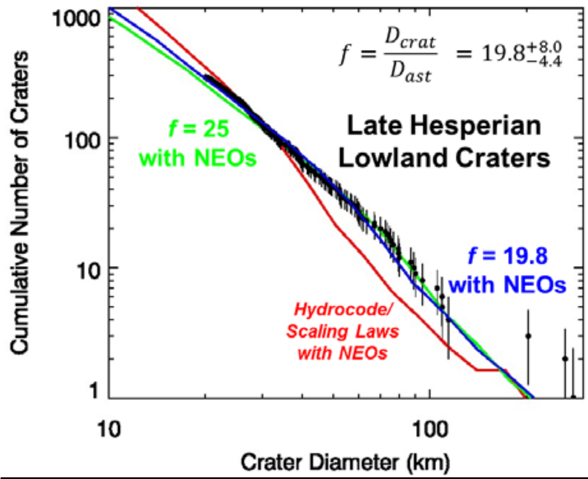


**Fig. 3.** Comparison between Martian craters (black) and modified NEO SFD. Asteroid diameters were (blue) multiplied by $f = 19.8$, (green) $f = 25$, and (red) input into a crater scaling law designed to match hydrocode results.

for $D_{crat} < 30$ km. An arguably superior fit to the larger craters comes from ignoring this feature (e.g., green line, $f = 25$, which is well within 1σ errors).

**Summary.** To our surprise, we found $f \sim 24$ produces excellent matches for the crater SFDs examined on the Moon, Venus, and Mars. If we assume this value holds for Earth as well, the projectile size needed for Chicxulub (~180 km / 24) and Popigai (~100 km / 24) are $D_{ast}$ ~7.5 and 4.2 km, respectively. _These values reproduce those derived from Ir/Os estimates_.

Moreover, the fits are probably not flukes; "fake" NEO SFDs designed to reproduce the craters in **Figs. 1-3** with hydrocode scaling yield shapes inconsistent with them being derived from the inner/central main belt SFDs via Yarkovsky drift [6, 11].

This leads us to suggest that hydrocodes are overestimating the projectile sizes needed to make large craters on the terrestrial planets. This is curious, but up to now there has been no way to test them against Popigai/Chicxulub-sized or larger blasts; their main calibration targets have instead been smaller laboratory shot experiments and nuclear blasts.

**Implications for Earth**. These results have many implications, only a few which we describe here:

- The ages of Chicxulub (~66 Ma) and Popigai (~35 Ma) craters are not anomalously low, but instead are consistent with the expected impact rates for ~7-8 and ~4 km NEOs on Earth, respectively [e.g., 5].
- Our predicted production rate of very large terrestrial craters is consistent with Earth's crater record after one considers that only ~8-15% of Earth's surface have identified $D_{crat} > 2$ km craters (e.g., zero found in high erosion rate regions like ocean floors, etc.).
- More Chicxulub-sized blasts over time imply more extinction events or that many large impacts actually less lethal than predicted. This difference sets up testable predictions for future work.

**A Younger Surface Age for Venus**. The results in **Fig. 2** allow us to compute a revised surface age for Venus. To get the long-term impactor flux, we first examined the Moon. LRO/Diviner data can be used to predict the ages of $D_{crat} > 20$ km lunar craters over the last ~1000 Ma [e.g., 12]. They yield a production rate of 2.07 (+0.57, -0.75) × $10^{-15}$ $km^{-2}$ $yr^{-1}$ over 270 Ma. This age limit was chosen because lunar impact rates are changing near this time; overall, the flux ≲ 270 to 400 Ma is ~3× higher than between ~400-1000 Ma.

Next, we used numerical integrations results from [13-14] to find the velocities "at infinity" ($V_\infty$) for terrestrial and lunar impactors entering the Earth/Moon system. Combined with equations from [14], we found the ratio of objects hitting the Earth vs. Moon is 20.9. This means Earth's $D_{crat} > 20$ km crater production rate is 3.23 (+0.90, -1.14) ×$10^{-15}$ $km^{-2}$ $yr^{-1}$ over 270 Ma, provided $f$ is the same for both worlds. Both estimates are consistent with those in the literature [e.g., 7, 16].

Again using [13-14], we found the ratio of impacts on Venus to the Earth and Moon is 1.32 and 27.6, respectively. This yields a $D_{crat} > 20$ km crater production rate for Venus of 4.72 (+1.67, -1.31) ×$10^{-15}$ $km^{-2}$ $yr^{-1}$ over 270 Ma. Because both the Moon and Venus use $f \sim 24$, the lunar impact rate can be easily scaled to get Venus' impact rate. Applying these values to our **Fig. 2** fit yields a Venus surface age of ~180 (+70, -50) Ma. This value is younger than previous estimates (e.g., ~500-750 Ma; see [17]).

There are indications that the lunar/terrestrial impact flux has been modestly higher over the last ~120-150 Myr than the last ~270 Myr [e.g., 12, 16]. The use of such values yields an even younger surface age of ~150 (+50, -40) Ma. The same age is found if we use the current NEO impact flux (and $f \sim 24$) for ~150 Ma.

A younger surface age has major implications for Venus' internal history [18]. It could make recent volcanism on Venus less surprising [e.g., 19], while providing us with clues on whether or not Venus' surface was globally resurfaced ~150-180 Ma [e.g., 20].

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