A POTPOURRI OF RELATED CRATER CATALOGING: FROM FITTING ELLIPSES TO NEW BASEMAPS TO CRATER PRODUCTION FUNCTIONS.

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Overview: This abstract, and presentation at the 2018 Planetary Crater Consortium, focuses on crater cataloging on the Moon and Mars, details of some recent work on the methods of the crater cataloging, and work using the craters to reconstruct and possibly reconcile differences between different researchers on a key tool in crater analysis: the production function.

Background: During the years 2007–2012, I worked to construct a global Mars impact crater database that had the stated goal of being a complete sample of all impact craters with diameters $D \geq 1$ km, and it numbered ≈375k craters $D \geq 1$ km, or 640k craters in total [1,2]. During the years 2012–2018 (and ongoing as new projects arise), I did the initial work for a similar crater catalog for the Moon that contains over two million entries (~1.1 million $D \geq 1$ km), and this effort was awarded a NASA PDART to expand it to include similar information to the Mars database effort.

A significant difference between the way I versus most other researchers identify impact craters is that I trace crater rims, giving at least 5 points along the rim (and usually many more) from which to fit a circle and an ellipse. Most other efforts are limited to two points (a chord to define a diameter), three points (to uniquely define a circle), or five points (which could be used to uniquely define an ellipse but most often is not). Historically, and still most often today, researchers will not derive ellipse parameters and if they do, those are only done for craters that are "obviously" elliptical. Because at least five points are needed to define an ellipse, my identification method allows all craters in the database to be fit to both circles and ellipses. Ellipse fits are important because they add parameterized information about the shape of the impact crater, increasing the information from three parameters (center latitude, center longitude, diameter) to five (center latitude, center longitude, major axis, minor axis, and tilt). However, recent work has shown that the ellipse fits may be biased (both due to identification inaccuracies and the equations used to fit an ellipse), so I will **first** discuss efforts to minimize and remove some or all of that bias.

Separately, I am funded to examine craters on youthful surfaces and the rims of large basins on Moon, Mars, and Mercury from which to build new empirical production functions (PFs). Now that the lunar crater database is practically complete, I am transitioning to the analysis phase of that work and beginning the Mars work. Due to various issues that have been raised about the Mars crater database (see [3]), I have begun a Mars database "v2" effort, beginning with the youthful Amazonis and Elysium regions of Mars for the PF effort. This database is being constructed from fully controlled Context Camera mosaics that we have built, and so the **second** component of this abstract and presentation discusses how those mosaics are constructed and how they are far superior for crater identification to the best-available THEMIS mosaics when the "v1" database was made.

The **third** component of this abstract and presentation is about the very preliminary results in constructing a new, empirical crater PFs for Moon and Mars, and the approach to Mercury.

Ellipses: All of the crater catalogs that I have built have used what is known as a direct ("DIR") method to fit an ellipse, popularized by [4] in 1997. It was slightly corrected in 1998 [5], but the corrections do not affect this work. However, the mathematics community has advanced since then, and advanced since the Mars database was originally constructed. In particular, work by [6] in 2012 clearly demonstrated that DIR methods are extremely biased when fitting ellipses to noisy, incomplete data (*i.e.*, if a complete ellipse is drawn between 0° and 360°, then an incomplete ellipse is a smaller segment of arc, such as 45°–120°). This bias is most often manifest as major and minor axes that are both smaller than the best-fit circle diameter, which should be impossible. This theoretical issue comes into practice with craters because rims are often incomplete and do not always span all 360° of arc. An additional issue is that, as with any manual effort, the rim traces I make are not perfect, and small, ~pixel-scale offsets occur which can bias the ellipse fits.

I have completed an effort to remove the bias from the DIR ellipse fits by using a recently published AML (approximate maximum-likelihood) technique [7]. This new code is significantly slower (can take ~1 second to run for ~1000 points, instead of milliseconds) because of the significant amount of matrix manipulation and iteration. However, it is (a) much less biased, and (b) returns standard errors for each fit parameter in addition to a visual confidence region. See Fig. 1 for an example.

I have begun an effort to mitigate the bias in the manual rim traces by developing a "rim-snapping" code. This code takes an image of the crater, a known sun direction, the manual rim trace, and searches radially near each point in that trace for the maximum brightness transition that should be indicative of the exact rim location. The code is still in the developmental stage, but it shows promising results.

Fully Controlled CTX Mosaics of Mars: Over the past year, I, along with R. Hoover and M. Kirchoff, have developed a robust and mostly automated workflow to produce fully controlled CTX mosaics of Mars at 6 m/pix. The current best fully controlled basemaps of (most of) Mars is THEMIS Daytime IR at 100 m/pix. CTX is visible light instead of infrared – infrared can make geologic interpretation difficult and even erroneous in some cases – and the much higher spatial resolution of CTX allows one to see many features that before were hidden. CTX currently covers 97.3% of Mars, so the dataset and mosaics are highly useful for the nascent process of creating a v2 Mars crater database, especially when the goal is to identify and accurately measure $D \geq 0.5$ km craters in the youthful terrain for the production function work.

New Empirical Production Functions: I am funded through an SSW to develop new, empirical crater production functions for $D = 0.5$–50 km for Moon and Mars, and $D = 5$–50 km for Mercury. This work is motivated by the fact that the two main PFs in use by the planetary science community disagree by factors of several in the critical $D \sim 2$–10 km range [*e.g.*, 8]. It is hoped that a new, independent investigation using modern datasets and modern techniques might determine which – if either – is more accurate and release a new tool to the community. The PF is a critical tool for it is against the PF that impactor populations are compared, that craters in certain regions are compared to determine erosion/modification, and they are used for modeling absolute ages of surfaces.

The new PFs are focused on regions that are relatively young (lunar maria, martian volcanic plains, hermean basin floors) for smaller impact craters, and the rims of large basins for larger craters (basin rims form a mostly cohesive unit and they are old so retain a record of larger impacts that have not yet had time to form on younger, volcanic terrain). Significant care is being made to avoid secondary impact craters, which is why the production functions will be truncated at the specified minimum diameters. They are truncated at the larger diameters to avoid small-number statistics.

As of the time of this abstract submission, lunar craters have been fully identified, and mapping is underway to ensure "clean" surfaces, removing features such as wrinkle ridges, rilles, montes, and large fields of secondary craters; additional classification is underway to further remove secondary craters and craters that are not superposed on the counting surface (*e.g.*, ghost craters). On Mars, crater identification and mapping has been completed for volcanic terrain, and crater classification is underway to again further remove secondary craters and craters not superposed on the surface. For Mercury, creation of fully controlled images is in progress upon which to identify the craters, following the tools we developed for CTX data of Mars.

References: [1] Robbins & Hynek (2012a) doi: 10.1029/ 2011JE003966. [2] Robbins & Hynek (2012b) doi: 10.1029/2011JE003967. [3] Robbins (2017) *PCC* Abs. #1703. [4] Fitzgibbon *et al.* (1997) doi: 10.1109/34.765658. [5] Halíř & Flusser (1998). [6] Szpak *et al.* (2012) doi: 10.1109/DICTA. 2012.6411722 [7] Szpak *et al.* (2015) doi: 10.1007/ s10851-014-0536-x [8] Neukum *et al.* (2001) doi: 10.1023/A: 1011989004263

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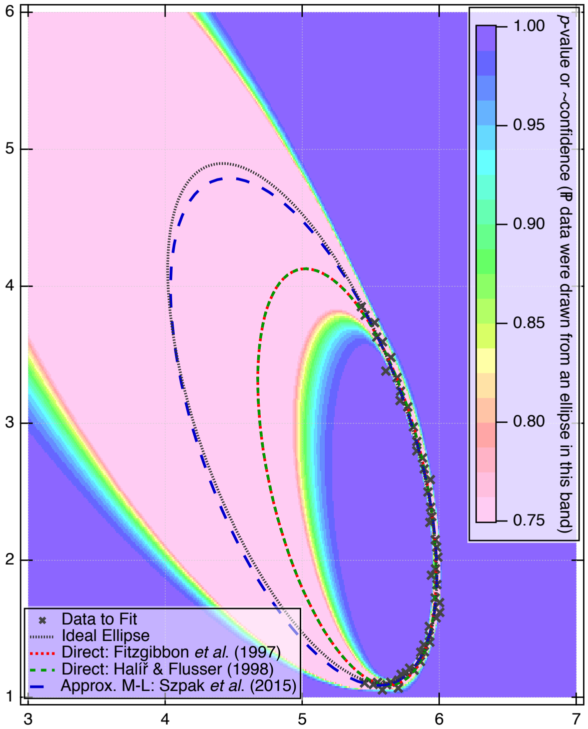

Figure 1: Example noisy, partial data drawn from a perfect ellipse and fit with three different algorithms. The perfect ellipse parameters are $\{x_0, y_0, D_{\max}, D_{\min}, \theta\} = \{5, 3, 4, 1.5, 110°\}$. The DIR methods fit the data as $\{5.3, 2.6, 3.1, 1.1, 103°\}$, while AML fit the data as $\{5.0 \pm 0.2, 2.9 \pm 0.3, 3.8 \pm 0.6, 1.5 \pm 0.2, 110 \pm 4°\}$. The background coloring is the *p*-value, roughly equivalent to a confidence interval. It can be interpreted as, for the pink region, being where the null hypothesis that the data were *not* drawn from an ellipse in that area can be rejected to 75% confidence. While the confidence region may seem large, keep in mind that the data are drawn only for ⅓ of the ellipse arc, and the AML fit is significantly better than DIR.