THE LUNAR CRATER CHRONOLOGY: HISTORY, CURRENT KNOWLEDGE, AND HOLES. S.J. Robbins[1]. [1]Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302. stuart@boulder.swri.edu

Introduction: Crater-based age modeling is the primary method of estimating surface ages across the solar system, and all are tied to the Moon from *Apollo* and *Luna* sample returns. Radiometric ages were determined for all landing sites with sample returns [1]. Crater densities on each sampled unit are assumed to represent the number of craters required for a terrain to be that radiometric age; this cratering chronology is usually expressed as the sum of all craters $D \geq 1$ km on a given unit, written as $N(1)$, and that density corresponds to the age. This process has a lengthy history with few recent revisions, but work on lunar cratering and dynamical modeling has cast significant doubt on whether established work is as robust as many assume. Additionally, long-standing gaps and requirements – such as the focus on $N(1)$ densities and using model production functions to estimate it – raise issues with tying the oldest terrains to post-LHB terrains to the youngest for a cohesive chronology.

Historic Approach and Work: Most work on the lunar crater chronology was completed by 1980 [2-9] after which summaries were produced [10-12]. This earlier work can be broadly characterized as numerous researchers or groups mapping sampled terrain and measuring the crater populations. These used images from the *Apollo* mapping cameras and *Lunar Orbiter*. From the six successful *Apollo* missions and two *Luna* sample return missions, approximately 11 chronology calibration sites were identified; these are locations with a crater density tied to a specific radiometric age. From this sparse sampling, which contained five points <1 Ga and six points 3.2–3.9 Ga, the "classic" lunar chronology function emerged, characterized as an exponential decline in cratering early in lunar history, followed by a linear rate thereafter (Fig. **1**A). The missing >3.92 Ga and gap of 1–3 Ga mean extrapolations are necessary in both and unconstrained in the former. Additionally, despite numerous researchers identifying different crater densities (Fig. **1**A/B), the values by the Neukum group [*e.g.*, 12] and the resulting fit is what most people use today. Only a few researchers have done any further work [13-16], while the most recent comprehensive work prior to 2014 only examined the most recent <1 Ga points [15].

Reanalysis by Robbins (2014): The crater chronology is typically considered to be well established by most researchers, despite the ranges of values in published crater data and the most recent radiometric results. Robbins [16] completed the first comprehensive examination of *all* chronology sites using digital crater measurement techniques and the recent, higher quality data that are now available.

Lunar Reconnaissance Orbiter Wide-Angle Camera mosaics were created at near-native resolution (~60 m/pix) of all the landing sites. For the three small crater calibration points (Cone, North Ray, and South Ray craters), Narrow-Angle Camera images were used (~0.5 m/pix). The surfaces surrounding each site were conservatively mapped to only include the unit that was sampled, and craters $D \approx 0.5$–10 km were manually measured. Each landing site was analyzed, and several comparison and consistency tests were conducted.

Overall, $N(1)$ of all units in this work generally agree with previous results or are larger (while still within the range of different published data, they are larger than [12,17]), indicating previous work undercounted or -estimated craters in light of the new data. This is attributed to: (a) earlier researchers did not always identify craters on the same unit as the landers, (b) the $N(1)$ points were often extrapolated from larger or smaller craters based on models and not directly measured, (c) the area occupied by secondary crater clusters was not excluded in previous work, and (d) poor-quality images were sometimes used that limited the ability to identify craters.

Neukum *et al.*'s [17] work is used by most, and their lunar chronology relating $N(1)$ and time T (in Ga) is $N(1) = \alpha(\exp(-\beta T) - 1) + \gamma T$ where $\alpha = 5.44 \cdot 10^{-14}$, $\beta = 6.93$, $\gamma = 8.38 \cdot 10^{-4}$. This function is defined for $N(1)$ *only*, so it is assumed that the impactor population has retained a constant size distribution. Hartmann *et al*. [13] proposed, based on lunar impact melts, *Apollo*-returned glass spherules, and Martian landslides, that the time-scaling function include a quadratic term, reflecting a decrease in the cratering rate over the past few Ga: $N(1) = \alpha(\exp(-\beta T) - 1) + \gamma T^2 + \delta T$.

This quadratic form was found via statistical tests to be a better fit than the original linear form, and so it was fit with these new data (Fig. **1**). After consideration of potentially questionable data points, the final fit parameters are: $\alpha = 1.79 \cdot 10^{-40}$, $\beta = 22.4$, $\gamma = 1.62 \cdot 10^{-4}$, $\delta = 1.04 \cdot 10^{-3}$. If one were to apply a dynamic correction for lunar apex/anapex cratering asymmetry [18], $\alpha = 6.23 \cdot 10^{-41}$, $\beta = 22.6$, $\gamma = 1.77 \cdot 10^{-4}$, $\delta = 9.10 \cdot 10^{-4}$.

Implications of Robbins' Chronology: The main qualitative consequences of these fit parameters, in comparison with Neukum *et al*. [17], are three-fold: (a) the smaller α indicates the formerly linear term, now quadratic, dominates over more of geologic time: instead of the exponential dominating for $T > 3.3$ Ga, its effect is $T > 3.6$ Ga. (b) The larger β term increases the exponential significantly such that there is a rapid increase in cratering as time into the past increases for as long as the function is valid, $T \leq 3.92$ Ga. (c) There are two points of intersection in the fits – 3.56 and 3.94 Ga – where surfaces have the same age at both, are older between, and are younger outside that range.

Figure **1**C illustrates how ages change from [17] to the new chronology. For example, a surface dated to 3 Ga [17] would move forward in time by 1.1 Gyr, providing a new model crater age of 1.9 Ga. This acts to stretch many geologic processes on Mars closer to the present day while compressing earlier history – such as the extent of the lunar LHB – in time.

While one interpretation of this work could be *this* is "*the* correct answer," a more conservative interpretation is that the lunar chronology is not nearly as well known as had been thought, and more work must be done to better constrain it. In addition, there are unresolved complications that require additional work.

Complication: Does the Terrain Match the Age? One assumption is the mapped area on which craters are measured is represented in the sample returns, and the derived radiometric age reflects the formation age of the crater-counting surface. This may not be accurate in many cases, for one cannot always assume that rocks are sourced locally. Indeed, the entire case for Copernicus crater being a chronology point is ejecta material from it was sampled by *Apollo 12*, over 400 km away from the crater. Elsewhere, Imbrium ejecta may significantly contaminate many sampled terrains.

Complication: Relying on *N*(1) and Extrapolation to Young Terrains. The size-frequency distribution of impact craters is assumed to follow a set function for chronology work. Unfortunately, there are at least three *different* functions in the literature [14,17,19]. This complication arises when one cannot directly measure *N*(1) and must extrapolate it from larger or smaller craters; to do this, a model *must* be used (and since three different models exist, they cannot all be correct). Not being able to measure *N*(1) directly arises from numerous factors, including crater saturation of the $D \approx 1$ km point, erasure due to impacts, contamination by secondary craters, and 1-km-diameter craters not having enough time to form on the terrain due to the small area or young age.

Complication: Two-Billion-Year Gap. There is a gap in samples that spans over two billion years of lunar history; it is three billion if one does not trust the Copernicus crater point. Even a single datum in this range would help to constrain the lunar crater chronology and would help to differentiate between different models. It could also help establish whether the exponential-linear or -quadratic fit is more accurate.

Moving Forward: While this is meant to provide an overview of the lunar chronology, it would not be complete without recommendations of how to better constrain it. One obvious way is simply more samples with better provenance: By measuring the mineralogical composition of pre-selected terrain on which new samples are gathered and then dating them, we could both close the 2–3 billion-year gap and be more confident that crater counts for a terrain accurately reflect the age of the sample meant to date it. A separate endeavor would be work on the *N*(1) requirement: The lunar chronology needs to be established for crater densities other than the arbitrary *N*(1), and/or the different models need to be reconciled. This is a significant problem in trying to tie the youngest lunar surfaces to the overall crater chronology.

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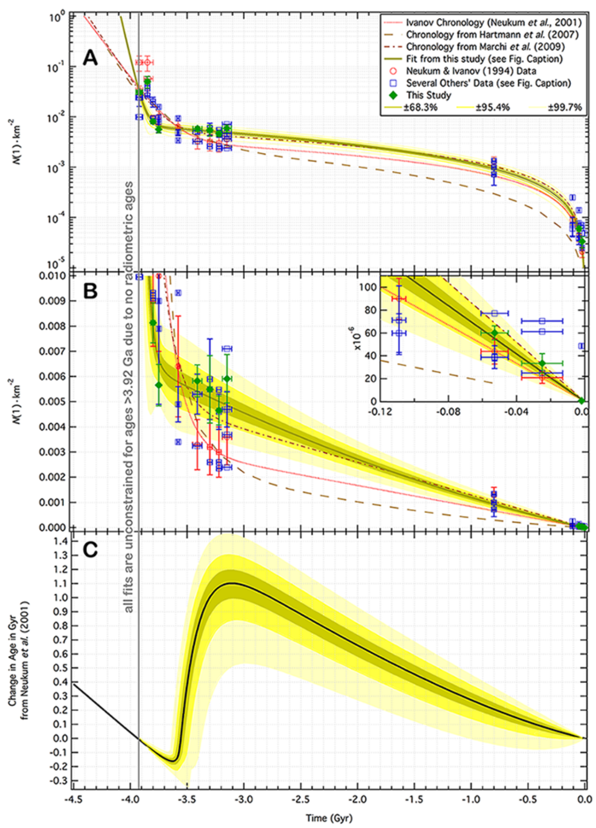

Figure 1: A and B— The canonical chronology [17] compared with revisions [13-14] and this work. Panel A shows the function on semi-log axes, while Panel B focuses on the recent cratering rate on a linear plot with the last 120 Myr inset. Data originally used by [10] are displayed with those from this study and several comparison works [3-5,8-11,14-15]. C— Difference between the new chronology and [17] as a function of age in the old chronology. 1σ, 2σ, and 3σ confidence bands are overlaid in yellow.