RE-EXAMINING THE MAIN ASTEROID BELT AS THE PRIMARY SOURCE OF ANCIENT LUNAR CRATERS. David A. Minton[1], James E. Richardson[1], and Caleb I. Fassett[2] [1]Purdue University Department of Earth, Atmospheric, & Planetary Sciences, 550 Stadium Mall Drive, West Lafayette, IN 47907 [2]Department of Astronomy, Mount Holyoke College, South Hadley, MA 01075 (daminton@purdue.edu)

Introduction. It has been hypothesized that the impactors that created the majority of the observable craters on ancient lunar highlands were derived from the main asteroid belt [1]. An alternative hypothesis, dubbed the E-belt hypothesis, postulates that a destabilized inner extension of the main asteroid belt produced only the sequence of basins beginning with Nectaris, along with the associated small craters [2]. We investigate these hypotheses with a Monte Carlo code called the Cratered Terrain Evolution Model (*CTEM*), which models the topography of a terrain that has experienced bombardment due to an input impactor population. We take advantage of recent advances in understanding the scaling relationships between impactor size (D_i) and final crater size (D_f) for basin-sized impact craters ($D_f > 300$ km) in order to use large impact basins as a constraint on the ancient impact flux on the Moon. Our goal is to test the hypothesis that impactors with the main belt asteroid SFD can produce the observed lunar highlands crater SFD, either in total, or for the more limited bombardment suggested by the E-belt hypothesis.

Our comparison data set is the catalog of all observed lunar craters with $D > 20$ km obtained using the Lunar Orbiter Laser Altimeter (LOLA) aboard the Lunar Reconnaissance Orbiter spacecraft [3]. Our impactor population uses the most up-to-date size-frequency distribution (SFD) for the main asteroid belt as obtained by the Wide-field Infrared Survey Explorer (WISE) [4]. For impactor sizes below 4 km, where WISE data becomes unreliable due to biases, we use the main belt SFD derived from a commonly-used collisional evolution model result [5].

We studied this problem in two steps. First we performed a series of regional simulations designed to determine the level of cratering needed to reproduce the total abundance of mid-sized (20–130 km) craters found on the lunar highlands. We next performed a similar set of runs for a global lunar surface using the observed lunar basins as a constraint.

The *CTEM* code. A powerful Monte Carlo code for studying the evolution of cratered terrains has recently been developed, called the Cratered Terrain Evolution Model (*CTEM*) [6]. We used *CTEM* to model the cratering history of the lunar highlands by bombarding simulated lunar surfaces with a main belt asteroid impactor population.

To determine the size of a crater from the parameters of a given impact event, *CTEM* uses the general solution to the transient crater volume scaling relationship given by Eq. 19 in Holsapple et al. (1993) [7], which includes both gravity and strength terms. For basin-sized impacts we use a recently developed scaling relationship for lunar basins based on hydrocode simulations, with a small adjustment to relate crustal annulus to rim-to-rim diameter [8].

Our adopted basin scaling relationship from [8] is defined for two mantle thermal profiles, a weaker, warmer upper mantle (TP1), and a colder, stronger upper mantle (TP2). Because the near-side crust is thinner and possibly warmer due to higher abundances of radioactive nuclides within the Procellarum KREEP terrain [9], this thermal dependence means that the size of basins that form on the near side tend to be larger than those on the far side for a given impactor size. This effect has been seen in data returned by the Gravity Recovery and Interior Laboratory (GRAIL) spacecraft [10]. We choose to apply either the TP1 or TP2 scaling relationship for a given crater with a 50% probability to reflect the hemispherical dichotomy of the Moon, and we only apply our basin scaling relationship for impactors with $D_i > 35$ km. As an example, using this relationship, the 930 km Orientale basin can be produced by a $D_i = 80$ km impactor with $v_i = 15 \text{ km s}^{-1}$ into cold upper mantle (TP2). The 1160 km Imbrium basin is produced by a similar impactor into warm upper mantle (TP1).

Lunar highlands simulations. The total amount of cratering for an individual simulation is parameterized by a quantity we define as the "production function averaged mass," $\bar{M}_{pf}$. This is the weighted mass of the entire production function at all sizes (excluding Ceres). A value of $\bar{M}_{pf} = 10^{22}$ g is equivalent to $N_{>10 \text{ km}} = 37$ using our main belt asteroid SFD.

Craters in the size range 90.5–128 km make for a useful diagnostic for determining how many impacts are required to match the regional lunar highlands cratering record, because the relative crater density, or R-value, for this size range is at a peak. For our regional lunar highlands simulations, we determine what fraction of runs for a given value of $\bar{M}_{pf}$ produce the observed $D \simeq 100$ km crater density. For our global simulations, we adopt the constraint that we must produce no more than 50 basins with $D_f > 300$ km, 1 with $D_f > 1200$ km (the size of Imbrium), and no basins larger than 2500 km (the size of SPA) [3, 11, 12].

We also performed a similar set of simulations to test the E-belt hypothesis. Under the E-belt hypothesis a destabilized primordial inner extension of the main asteroid belt, plus a small contribution from the main belt, could supply enough large impactors to produce the sequence of basins beginning with Nectaris [2]. We again performed a set of regional simulations to determine the total amount of cratering by a main belt-like SFD needed to reproduce crater abundances on Nectarian-age terrains. We then performed a global simulation to determine whether the basin constraint was met. For our regional runs we use the constraint that crater density on Nectaris basin is $\mathrm{N}(64) = 17 \pm 5$ and $\mathrm{N}(20) = 135 \pm 14$ [13]. Our global simulations use the constraint that we must produce no more than 14 basins [13], and none with $D_f > 1200$ km (the size of Imbrium).

For each set of conditions we performed 100–1000 *CTEM* simulations of the lunar surface. We tallied the countable craters in each simulation and determine how many of the simulations satisfy our constraints.

Results. For our total lunar highlands simulations, Fig. 1 shows the fraction that fit our constraints as a function of $\bar{M}_{pf}$. None of 500 runs with $\bar{M}_{pf} = 5 \times 10^{22}$ g satisfied the regional constraint, but $42 \pm 6.5\%$ of runs with $\bar{M}_{pf} = 6 \times 10^{22}$ g satisfied it. However, for $\bar{M}_{pf} = 5 \times 10^{22}$ g, only $1.6 \pm 0.6\%$ of runs satisfied the basin constraint, and only $0.6 \pm 0.35\%$ of runs satisfied it for $\bar{M}_{pf} = 6 \times 10^{22}$ g.

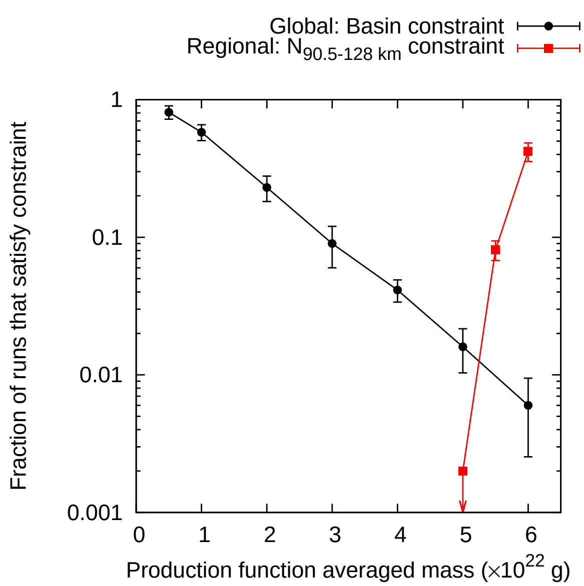

Figure 1: Fraction of *CTEM* total lunar highlands runs that satisfy our constraints as a function of production function averaged mass, $\bar{M}_{pf}$.

The E-belt simulation results are shown in Fig. 2. The fraction runs for a given value of $\bar{M}_{pf}$ that produced the observed values of $\mathrm{N}(20)$ and $\mathrm{N}(64)$ for Nectaris [13] are plotted as green triangles and red squares respectively. The $\mathrm{N}(20)$ densities were more constraining than $\mathrm{N}(64)$, and suggest values of $\bar{M}_{pf} = 1.75$–2.25×10^{22} g in order to reach the observed crater densities on Nectaris. For our E-belt global basin constraint, we require that runs produce no more than 14 basins with $D_f > 300$ km, and none with $D_f > 1200$ km. The fraction of runs for a given value of $\bar{M}_{pf}$ that satisfied the basin constraint is plotted as black circles in Fig. 2. Only $5 \pm 2.2\%$ of runs at $\bar{M}_{pf} = 1.75 \times 10^{22}$ g satisfied the basin constraint, and $1.5 \pm 0.4\%$ of runs satisfied it at $\bar{M}_{pf} = 2.25 \times 10^{22}$ g.

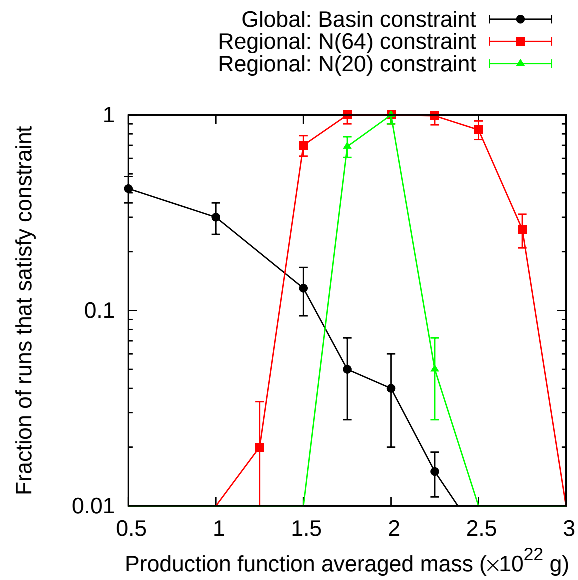

Figure 2: Fraction of *CTEM* E-belt runs that satisfy our constraints as a function of production function averaged mass, $\bar{M}_{pf}$.

Our results suggest that the main asteroid belt SFD is a poor model for reproducing the observed lunar highlands crater population. This is due to the relative abundance within the main asteroid belt of objects with which produce lunar basins larger than Imbrium compared with objects that produces $D_f \simeq 100$ km and smaller craters. This implies that the small body population that cratered the lunar highlands had a significantly larger ratio of objects that create mid-sized craters relative to megabasins than the modern main asteroid belt.

References

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