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Cratering saturation and equilibrium: A new model looks at an old problem

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ABSTRACT

Recent advances in computing technology and our understanding of the processes involved in crater production, ejecta production, and crater erasure have permitted me to develop a highly-detailed Cratered Terrain Evolution Model (CTEM), which can be used to investigate a variety of questions in the study of impact dominated landscapes. In this work, I focus on the manner in which crater densities on impacted surfaces attain equilibrium conditions (commonly called crater 'saturation') for a variety of impactor population size-frequency distributions: from simple, straight-line power-laws, to complex, multi-sloped distributions. This modeling shows that crater density equilibrium generally occurs near observed relative-density (R) values of 0.1–0.3 (commonly called 'empirical saturation'), but that when the impactor population has a variable power-law slope, crater density equilibrium values will also be variable, and will continue to reflect, or follow the shape of the production population long after the surface has been 'saturated.' In particular, I demonstrate that the *overall level* of crater density curves for heavily-cratered regions of the lunar surface are indicative of crater density equilibrium having been reached, while the *shape* of these curves strongly point to a Main Asteroid Belt (MAB) source for impactors in the near-Earth environment, as originally stipulated in Strom et al. [Strom, R.G., Malhotra, R., Ito, T., Yoshida, F., Kring, D.A., 2005. Science 309 (September), 1847–1850]. This modeling also validates the conclusion by Bottke et al. [Bottke, W.F., Durda, D.D., Nesvorný, D., Jedicke, R., Morbidelli, A., Vokrouhlický, D., Levison, H., 2005. Icarus 175 (May), 111–140] that the modern-day MAB continues to reflect its ancient size-frequency distribution, even though severely depleted in mass since that time.

1. Introduction

Cratered terrain on the solid surface of a Solar-System body provides us with a valuable record of that surface's bombardment history, material properties, weathering mechanisms and rates, and other endogenic processes. On 'old' surfaces with very low weathering rates (or other crater erasure mechanisms), the density of impact craters can reach equilibrium conditions, where for each new crater formed, a crater of roughly the same size is erased, and crater counts (over a given size range) level off as a function of time and further bombardment. The question as to *when* crater density equilibrium (also called 'saturation equilibrium' or just 'saturation') conditions occur and *what such conditions look like* is a long standing problem in the study of cratered surfaces, one which dates back to the intense studies conducted of the lunar surface during the build-up to the Apollo missions. Over time, the impact cratering community divided itself into roughly three viewpoints on this issue:

1. That variations observed in the shape of crater density curves for heavily-cratered regions of the Moon are indicative of a 'production population' (that is, a crater population that directly reflects its parent impactor population) and therefore, such regions are *not* in equilibrium. The fact that such variations are almost identically repeated on other inner Solar-System bodies, such as Mercury and Mars, lend credence to this viewpoint (Marcus, 1970; Woronow, 1977a,b, 1978; Chapman and McKinnon, 1986; Strom et al., 2005).
2. That the nearly identical *overall levels* observed in the crater density curves for heavily-cratered regions on Mercury, Mars, and the Moon (within a factor of 2 of each other) are indicative of these regions having reached an equilibrium state (saturation), and therefore, variations observed in the shape of these curves must be Poisson statistical in nature or indicative of endogenic crater erasure processes: that is, given time, such surfaces will eventually – given no additional endogenic crater erasure – show a straight-line (in log–log space) crater density curve (Hartmann, 1984, 1988, 1995; Hartmann and Gaskell, 1997).
3. That views (1) and (2) are both partially correct. On the one hand, these heavily-cratered regions do indeed represent crater density equilibrium conditions. On the other hand, even after

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equilibrium has been reached, variations observed in the crater density level as a function of crater size *continue* to reflect variations in the distribution of impactors which produced the crater populations: similar, but not identical, to a production population (Chapman and McKinnon, 1986).

Typical examples of the crater density curves under debate are shown in Fig. 1, courtesy of Chapman and McKinnon (1986).

One method for unraveling this problem is the use of scale models (either computer-generated or physical) to investigate the crater production and erasure process as a function of increasing crater density. The pioneering work for this sort of modeling was presented by Gault (1970), in which a physical model was produced to simulate a cratered terrain using a $2\ \mathrm{m} \times 2\ \mathrm{m}$ sandbox and a variety of small explosive and projectile devices to produce craters of various sizes on this model surface. Although of limited dynamic (crater-size) range, this model demonstrated that crater density equilibrium conditions generally occur at an overall density level of 1–10% of what Gault termed 'geometric saturation:' the crater density achieved when craters of the same size are placed rim-to-rim in a hexagonal close-packed arrangement. His modeling work also showed that when the impactor population has a cumulative log–log slope of <-2, equilibrium crater density conditions will be reached first by the smallest craters, then by larger craters, with the equilibrium crater population having a power-law slope of approximately -2 (not that of the steeper impactor population). Thus, he found that for a steeply-sloped impactor population (he did not explore the affects of a shallow-sloped impactor population), the relative age of the cratered terrain can be determined by comparing the position of the 'knee' in the crater density curve (the inflection point between the smaller craters, in equilibrium, and the larger craters, not yet in equilibrium) between different areas. Fig. 7, later in this work, shows a modeled example of this form of crater density equilibrium attainment. Gault's work thus seemed to support the second view described above, in that once an equilibrium crater density is reached, the crater population no longer follows its production population and stabilizes at roughly the same overall level

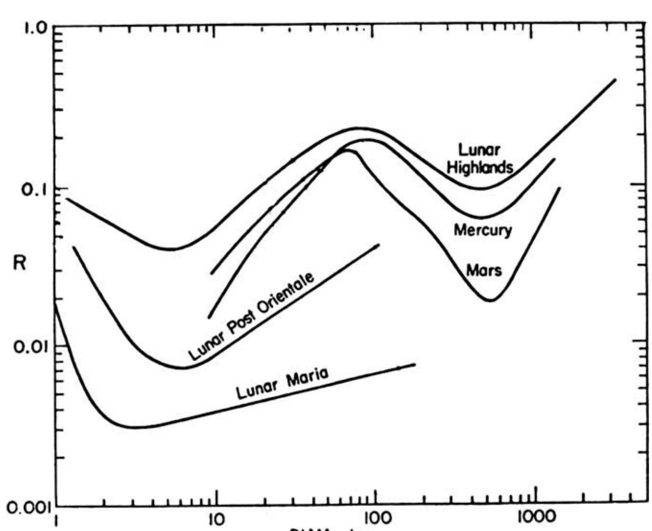

Fig. 1. A schematic representation of typical crater density curves for a variety of inner Solar System objects, taken from Fig. 18 of Chapman and McKinnon (1986). These, and subsequent crater density plots, are shown in standard R-plot format, as described in Arvidson et al. (1979). The upper three curves (for the lunar Highlands, Mercury, and Mars) represent older, heavily-cratered regions, while the lower two curves (for the lunar Maria and lunar Post Orientale regions) represent younger, less cratered regions.

(1–10% geometric saturation), as observed in heavily bombarded, small crater (<1 km) regions on the lunar surface (Hartmann, 1988; Hartmann and Gaskell, 1997).

The first attempt to model the crater density evolution of a planetary surface via computer was performed by Woronow (1977a,b, 1978) who, rather than modeling complex topography in three-dimensions, developed a Monte-Carlo method for creating and erasing representative, circular, crater 'rims' in two-dimensions only; that is, a geometric model. Limited by the computer technology of that time, Woronow's models were lacking both in geometric resolution (monitoring only selected points around each crater's rim) and in impactor size range (having dynamic ranges of only 16 or 32 between the smallest and largest impactors). Because of these limitations, Woronow's models displayed equilibrium crater density levels that are far above (by an order of magnitude or more) the crater density levels actually observed on heavily cratered surfaces, and hence seemed to support the first view described above: that heavily cratered surfaces in the inner Solar System have not yet reached equilibrium and therefore continue to display a production population. About a decade later, however, Chapman and McKinnon (1986) revisited Woronow's Monte-Carlo based, geometric crater-rim modeling technique, utilizing higher rim resolutions and a much larger dynamic crater-size range. Their work demonstrated a different conclusion. When fully circular crater 'rims' are monitored and a sufficient dynamic impactor range is employed (a factor of 128–200 in their work), modeled crater density equilibrium levels are (a) quite close to those actually observed in heavily-cratered regions, but (b) will continue to mimic, or follow variations present in the parent impactor population. Thus, the work of Chapman and McKinnon (1986) seemed to support the third viewpoint described above.

The first attempt to computer-model the evolution of a cratered terrain in three-dimensions was performed by Gaskell (1993), Hartmann and Gaskell (1993, 1997), using a fractal-based digital elevation map (DEM) model which monitored the changing landscape (as successive craters were emplaced) on a variety of fractal scales. Rather than scaling from impactor to crater size, the model emplaced craters directly, using a variety of straight-line power-law distributions. The ejecta coverage produced from each crater was computed by estimating the volume excavated by each crater and distributing it around the crater such that the resulting ejecta blanket exhibited a -3 power-law slope with distance from the crater rim; in effect, simulating gravity-scaled cratering (see Section 2.3). For both their medium-sloped 'primary population' (-1.83 cumulative power-law slope) and steeply-sloped 'secondary population' (-3.5 to -4.0 cumulative power-law slope) of craters, Hartmann and Gaskell (1997) showed that crater density equilibrium occurs at roughly the same overall level as that observed on actual heavily cratered surfaces, and that the resulting crater population tends to follow a cumulative power-law slope of roughly -1.83 even when the production population is steeper. This work thus supported the findings of Gault (1970) and seemed to support the second viewpoint described above, in that once an equilibrium crater density is reached, the crater population no longer follows a production population, and stabilizes at roughly the same overall level. However, shallow-slope impactor populations (*i.e.* >-1.83 cumulative power-law slope) were not investigated. Despite its sophistication, the primary drawback of this model was the lack of automatic (computer) crater counting, which severely limited the number of model runs and the number of time steps within each model run, for which crater counts could be manually performed – thus limiting its use to only a few specific case studies.

In this current work, I present a new Cratered Terrain Evolution Model (CTEM) which takes advantage of modern computing tech-